Beam Stability Requirements for Light Sources

R. Hettel, SSRL

1. SR beam parameters
2. SR beam line configurations
3. Stability criteria for storage rings
4. SR sensitivity to electron parameters
5. Electron beam properties
6. Stability in phase space
7. Stability time scales and averaging
8. Photon-electron relationships
9. Intensity stability
10. Photon energy stability and resolution
11. Timing and bunch length stability
12. Lifetime
13. Summary of stability requirements for storage rings
14. Stability in linac FELs and ERLs

    ring FELs, optical klystrons, Thomson scattering, etc. not considered
15. Conclusion

Beam Stability Criteria for SR Experiments

Stability requirements depending on particular experiment, including:

- beam line optical configuration
- sample size
- measurement technique and instrumentation
- data acquisition time scale
- data averaging and processing methods

Nevertheless, generic stability requirements can be estimated from criteria common to many experiments

Beam Stability Criteria for SR Experiments – cont.

Sources of photon beam instability can be divided into 2 categories:

- those associated with beam line optical components and experimental apparatus

  the beam line staff's problem!

- those associated with the electron beam

  the accelerator staff's problem!

Will focus on accelerator stability in this course

SR Beam Parameters

Photon beam parameters of interest to experimenter include:

- intensity at the sample
- position and pointing accuracy on small apertures and samples
- angle and divergence at optical components and sample

  contribute to resolution of energy and scattering angle

- energy and energy bandwidth

  contribute to energy resolution of experiment

- photon pulse time-of-arrival and bunch length

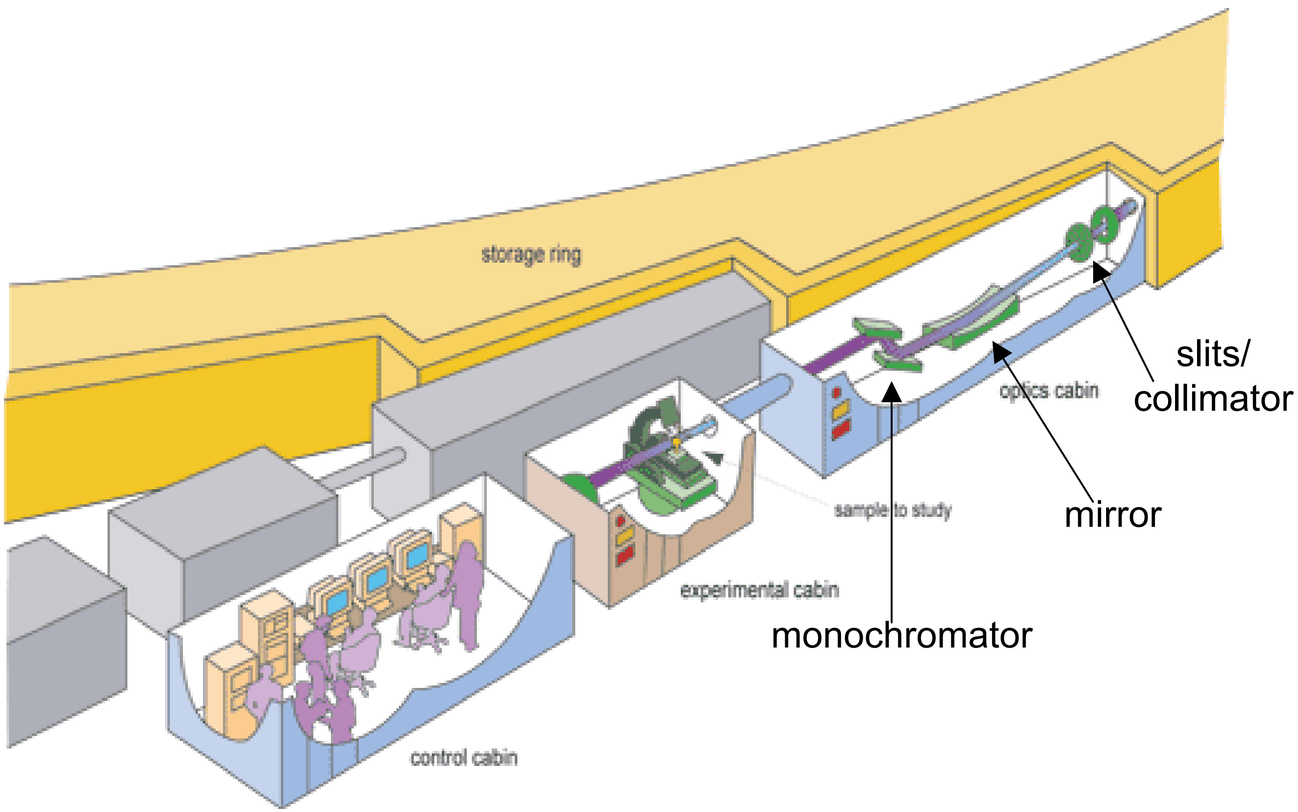
  for timing experiments

- polarization
- coherence

Examples of SR experimental methods and beam line configurations…

(Caveat emptor: the following is a simplified interpretation of sophisticated SR experimentation by an accelerator person…)

SR Generic Beam Line



could be more apertures (slits, etc) than shown

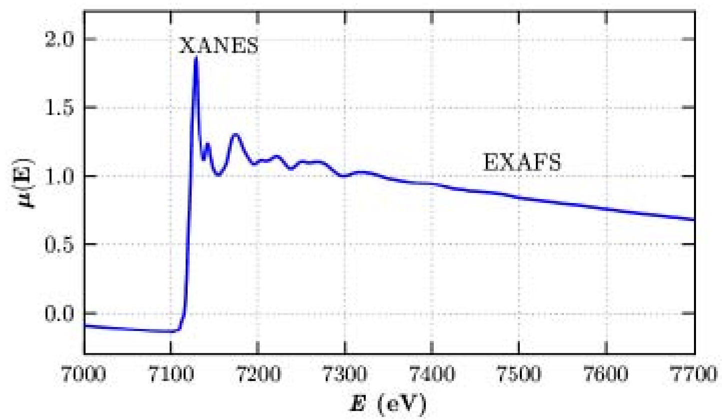
X-ray Absorption Spectroscopy

X-ray Absorption Fine-Structure (XAFS) is the modulation of the x-ray absorption coefficient at energies near and above an x-ray absorption edge. XAFS is also referred to as X-ray Absorption Spectroscopy (XAS) and is broken into 2 regimes:

XANES	X-ray Absorption Near-Edge Spectroscopy
EXAFS	Extended X-ray Absorption Fine-Structure

which contain related, but slightly different information about an element's local coordination and chemical state.

Fe *K*-edge XAFS for FeO:

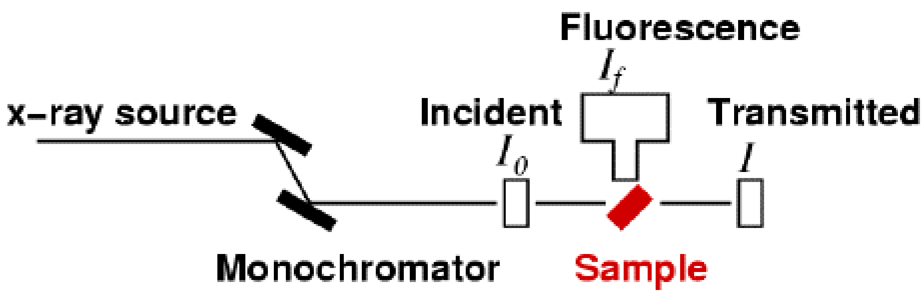


XAFS Characteristics:

- local atomic coordination
- chemical / oxidation state
- applies to any element
- works at low concentrations
- minimal sample requirements

from M. Newville, CARS, U. Chicago, 2002

XAS Beam Line



XAS measures the energy dependence of the x-ray absorption coefficient $\mu(\mathrm{E})$ at and above the absorption edge of a selected element. $\mu(\mathrm{E})$ can be measured two ways:

Transmission: The absorption is measured directly by measuring what is transmitted through the sample:

$$\begin{aligned} \mathbf{I} &= \mathbf{I}_0 \mathrm{e}^{-\mu(\mathbf{E})\mathrm{t}} \\ \mu(\mathbf{E})\mathrm{t} &= \ln(\mathbf{I}/\mathbf{I}_0) \end{aligned}$$

Fluorescence: The re-filling the deep core hole, is detected. Typically the fluorescent x-ray is measured.

$$\mu(E) \sim I_f / I_0$$

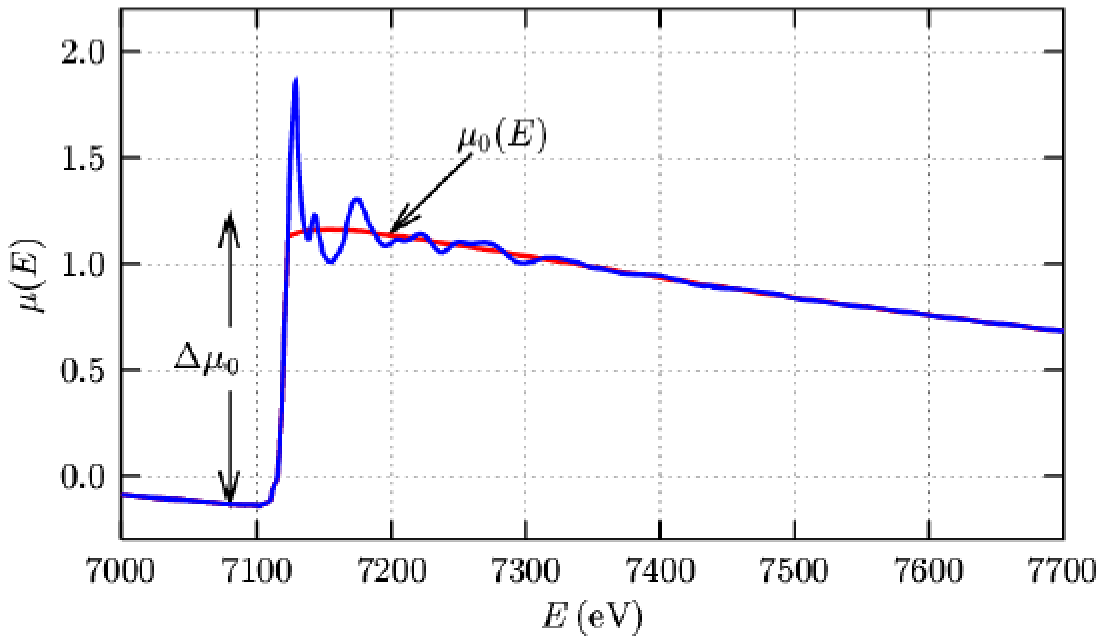
from M. Newville, CARS, U. Chicago, 2002

XFAS Measurement

We're interested in the energy-dependent oscillations in $\mu(\mathrm{E})$, as these will tell us something about the neighboring atoms, so define the EXAFS as:

$$\chi(\mathrm{E}) = \frac{\mu(\mathrm{E}) - \mu_0(\mathrm{E})}{\Delta\mu_0(\mathrm{E}_0)}$$

We subtract off the smooth *"bare atom" background* $\mu_0(\mathrm{E})$, and divide by the *"edge step"* $\Delta\mu_0(\mathrm{E}_0)$ to give the oscillations normalized to 1 absorption event:



from M. Newville, CARS, U. Chicago, 2002

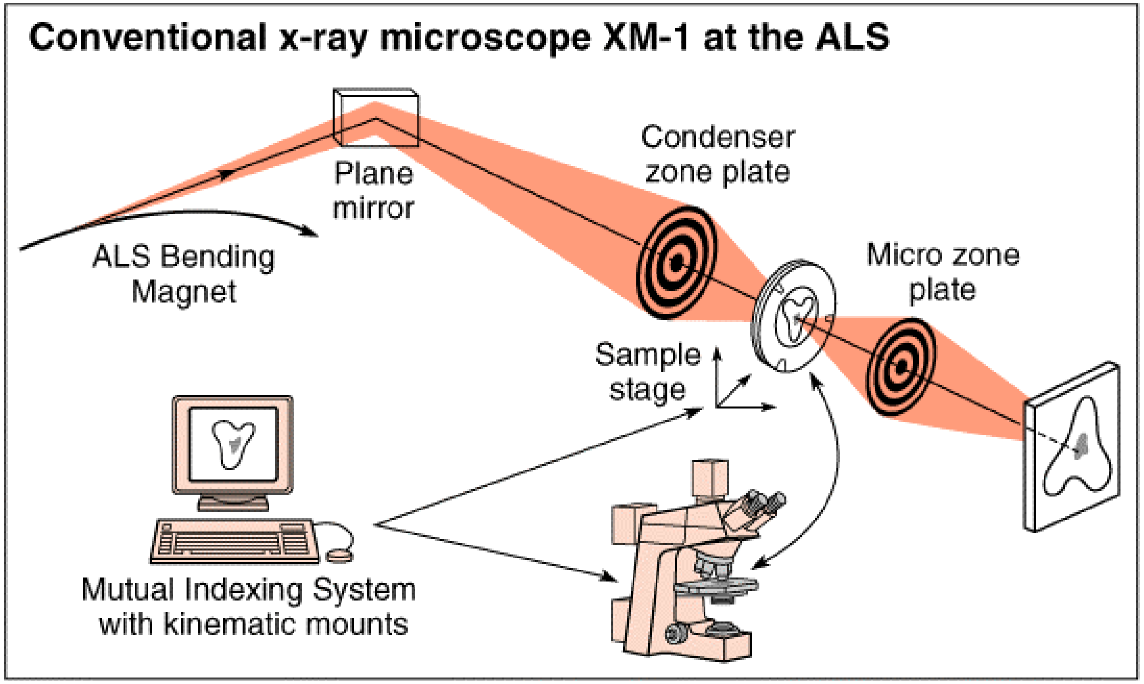
SR requirements:

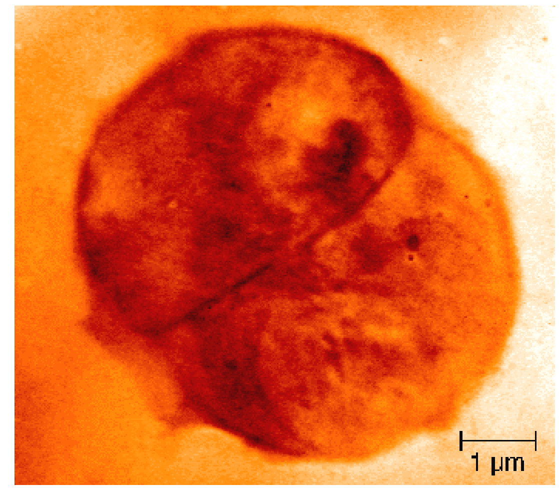
intensity stability: **10^{-3}**

energy resolution: **10^{-4}**

X-ray Microscopy and Micro-diffraction

Focus spot size to micron level to examine single micron-sized structures





60107003 XBD 9602-00404.BIM

white or monochromatic light, 100-1000 eV

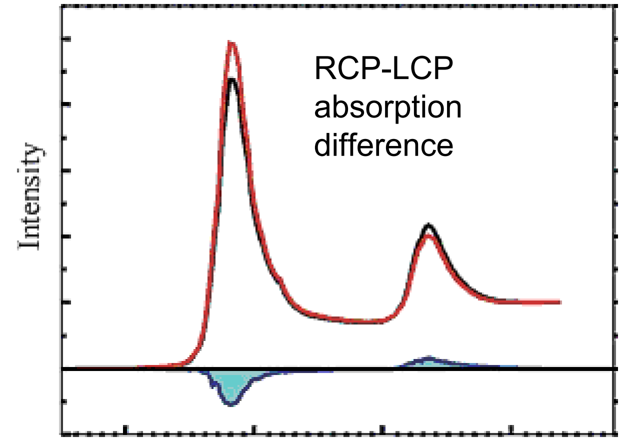
SR requirements:

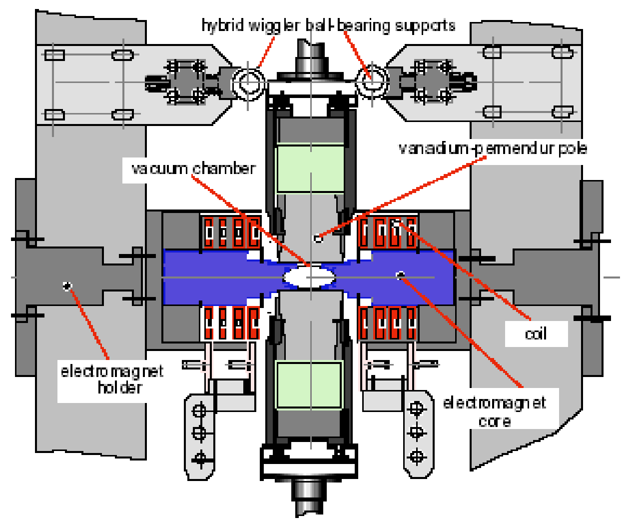
intensity stability: **10^{-3}**

position stability: **~1 µm**

Circular Dichroism Spectroscopy

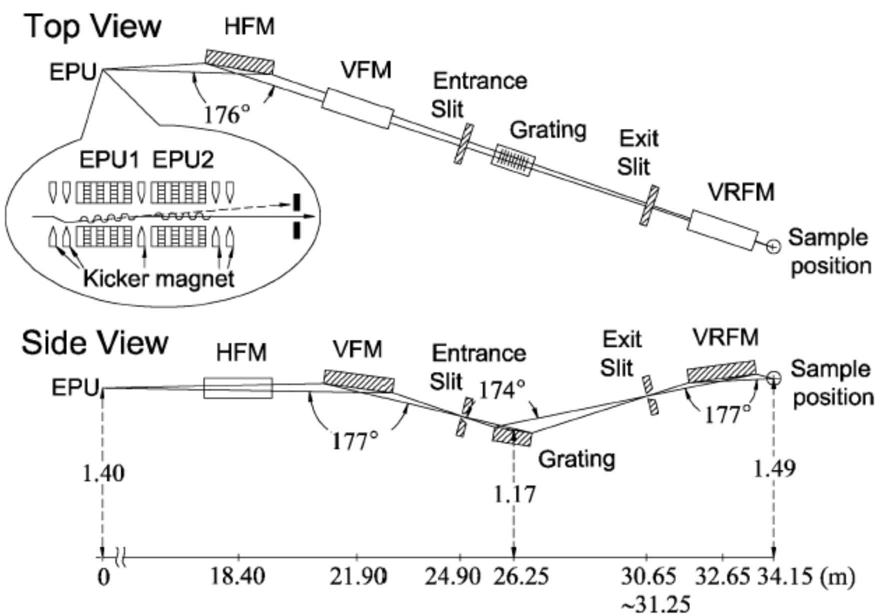
- Measure very small differences (**10^{-3}, trending to 10^{-4}**) in absorption of left- and right-handed circularly polarized light by optically active material. Yields information of structure of biological macromolecules and magnetic materials (i.e. magnetic domain boundaries)
- Switch between RCP and LCP either by switching beam between 2 EPUs, or by switching ID polarization (both cause stability problems)
- Fast switching improves immunity to orbit noise
- Very small slit apertures (10 μm)
- Position-sensitive focusing monochromators (spherical grating)





100 Hz swithched elliptically polarized wiggler at NSLS

Circular Dichroism Beam Lines

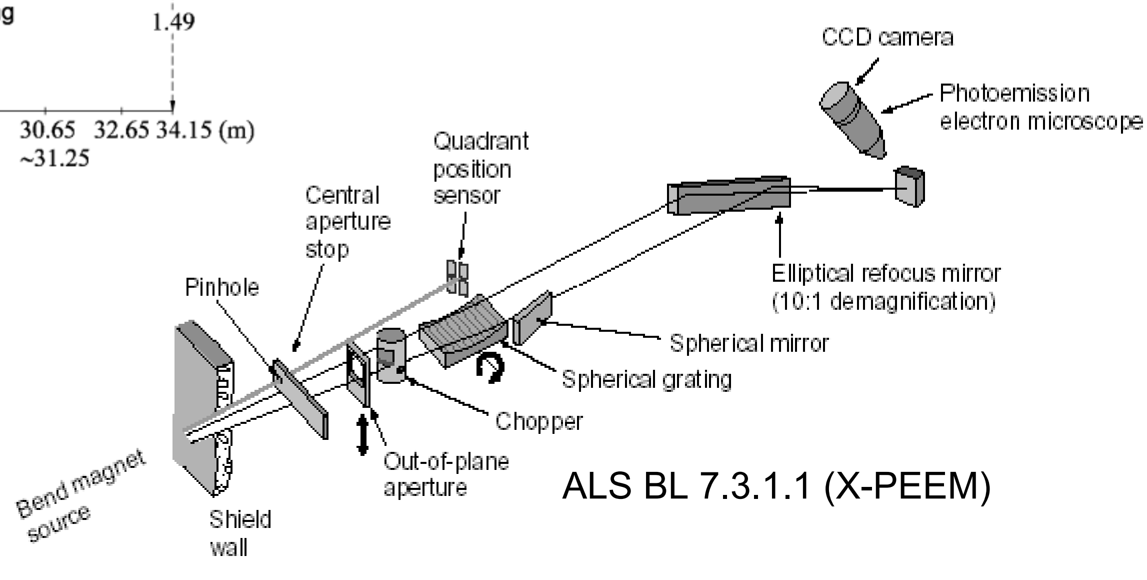


PLS EPU6

SR requirements:

intensity stability: <**10^{-4}**

position stability: **~1 μm**

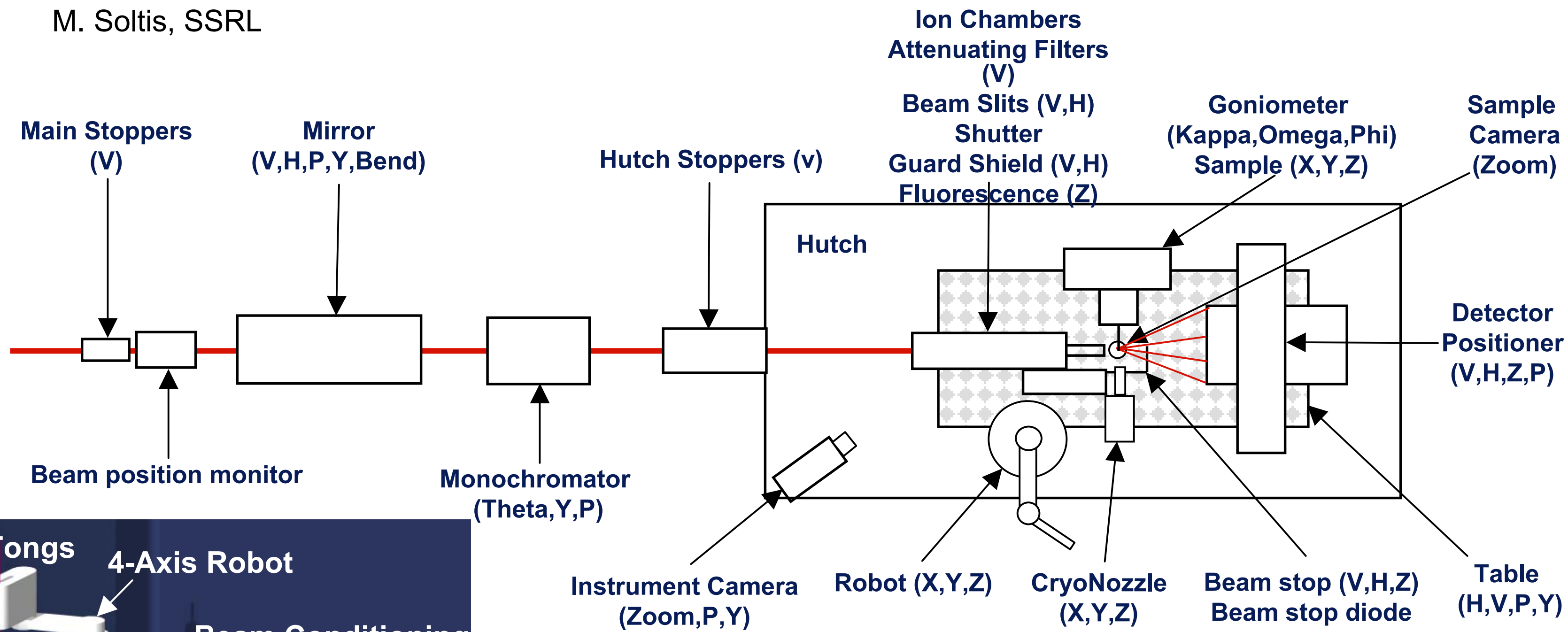


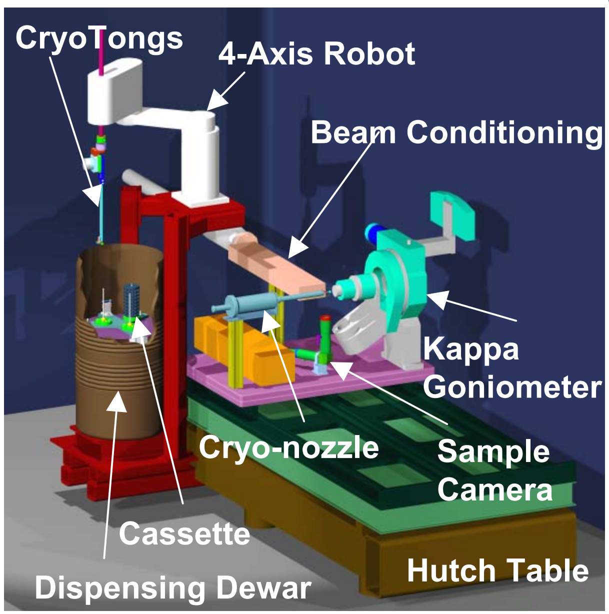
ALS BL 7.3.1.1 (X-PEEM)

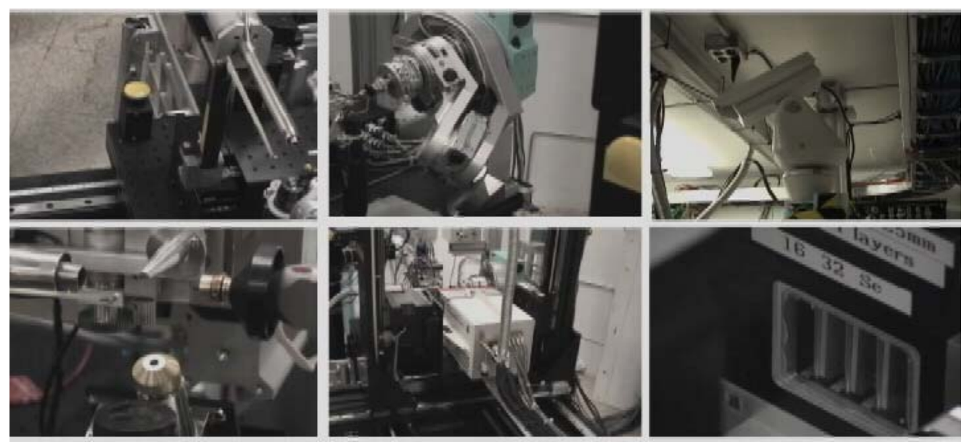
Schematic layout of Branchline 7.3.1.1.

Macromolecular Crystallography Beam Line

M. Soltis, SSRL

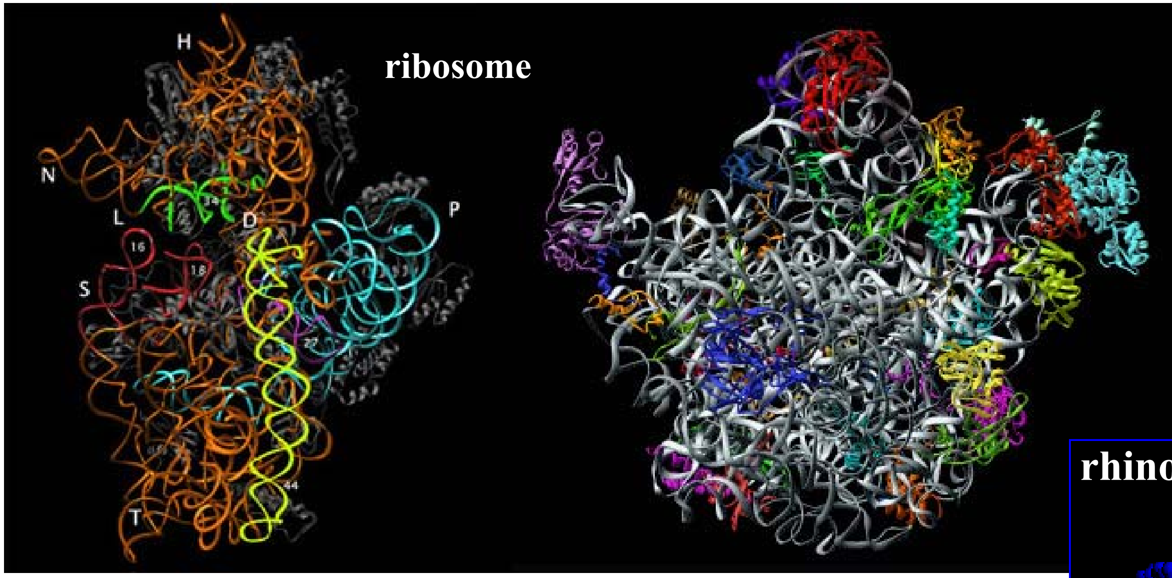


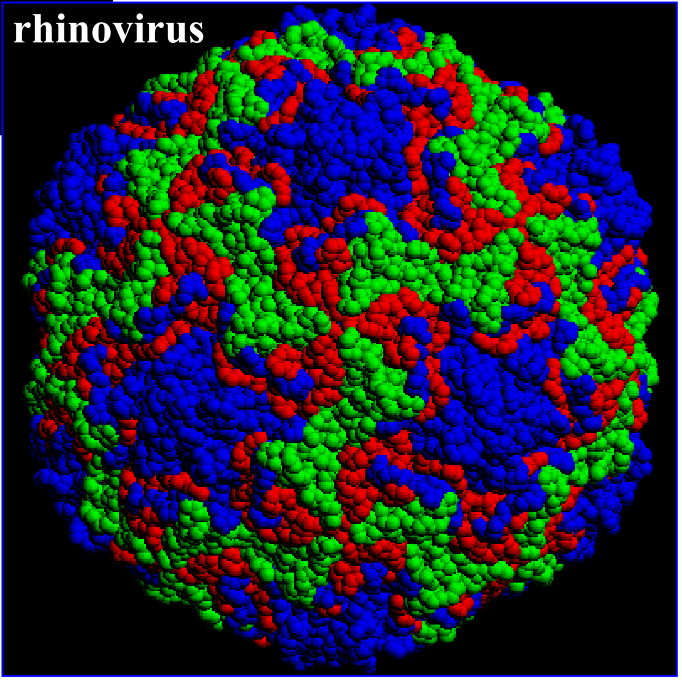


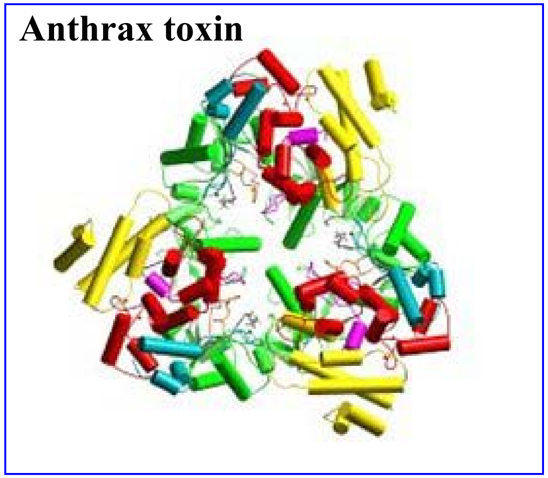


Crystal Structures

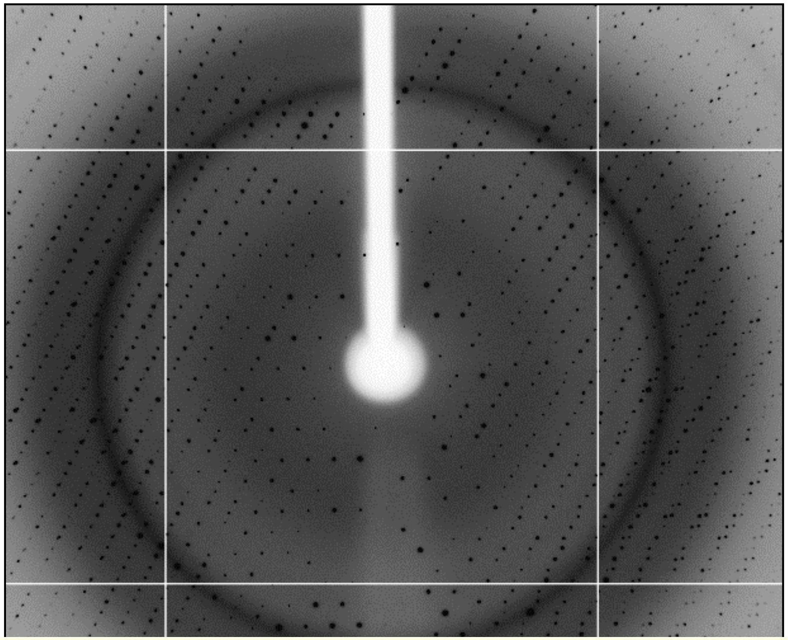
M. Soltis, SSRL







Macromolecular Crystal Diffraction Patterns



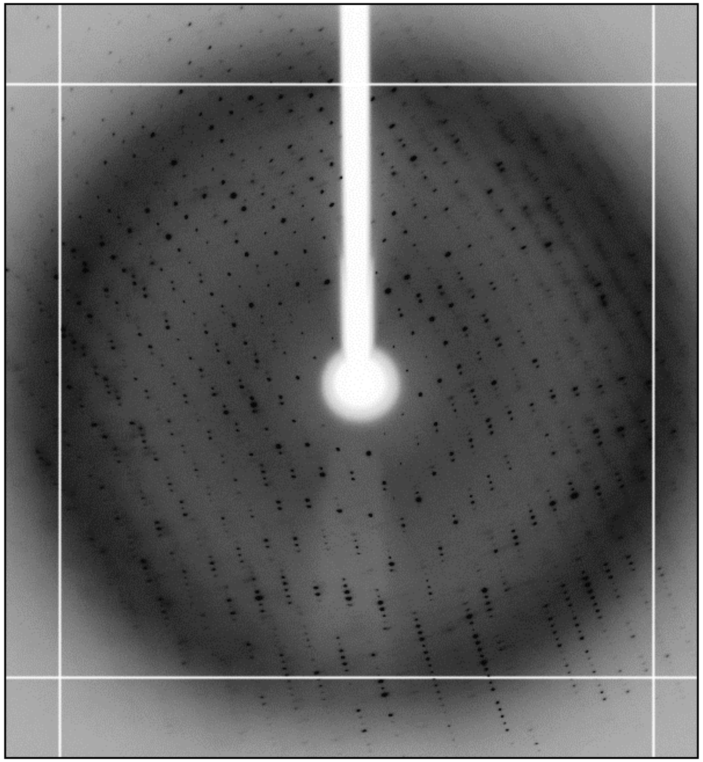
low mosaicity crystal

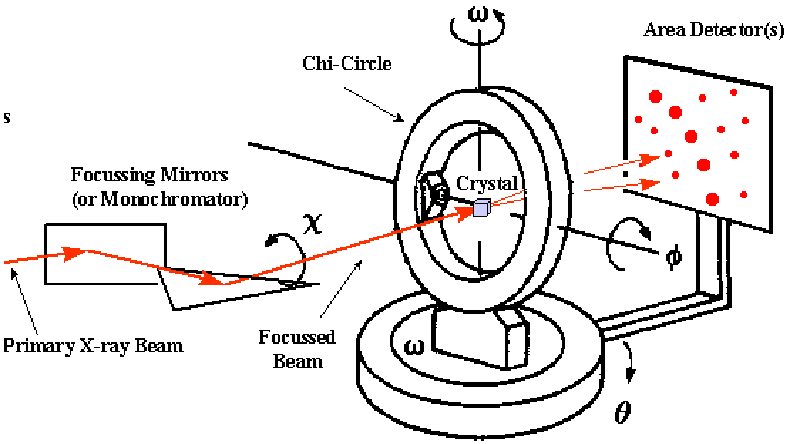
SR requirements:

intensity stability: **10^{-3}**

energy resolution: **10^{-4}**

high mosaicity crystal





4-Circle Goniometer (Eulerian or Kappa Geometry)

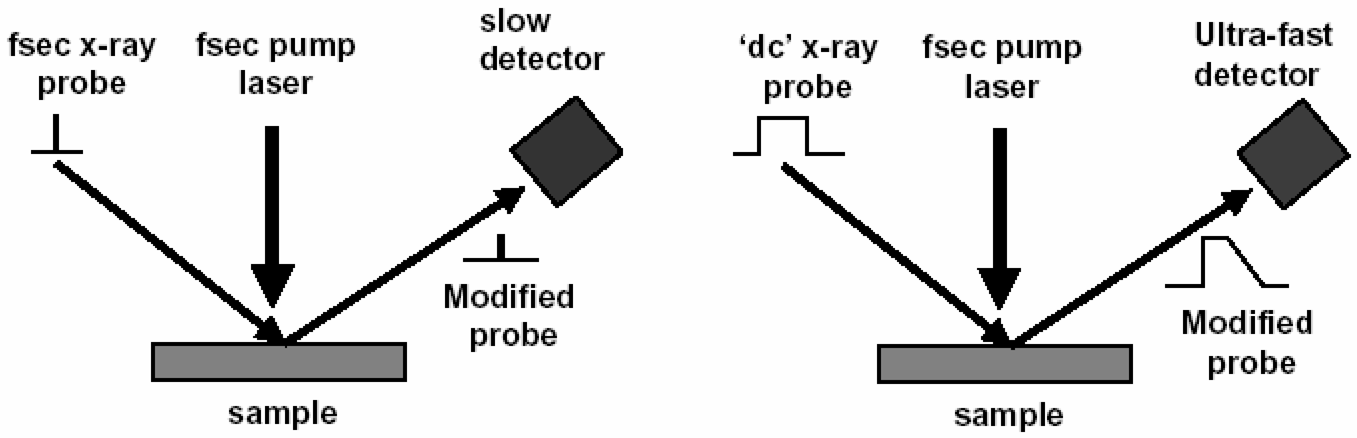
Femtosecond X-ray Spectroscopy and Diffraction

H. Padmore, ALS

Goal: measurement of structure on the fundamental time scale of a vibrational period ~100 fs

Research areas: ultrafast phase transitions, chemical reactions, biological processes

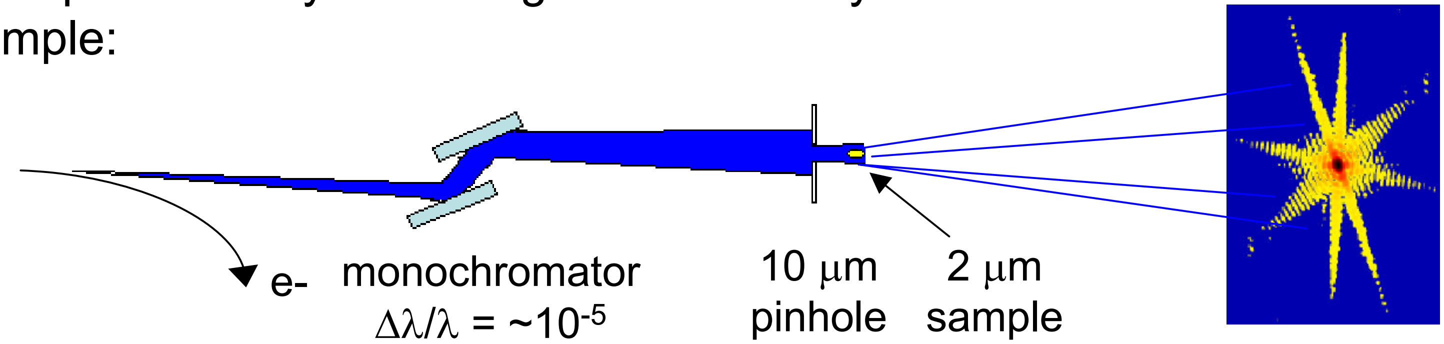
Probes: x-ray diffraction; ordered systems, structural phase transitions
spectroscopy; disordered/complex materials, chemical reactions



Timing stability requirement: pump-probe timing synchronization **< ~50 fs**, or else be able to measure actual shot-shot synchronization to that level

Coherence Experiments

Speckle pattern produced by scattering of transversely coherent photons in sample:



Longitudinal coherence length > sample thickness to obtain coherent speckle pattern

Longitudinal coherence length increased using narrow bandwidth monochromator:

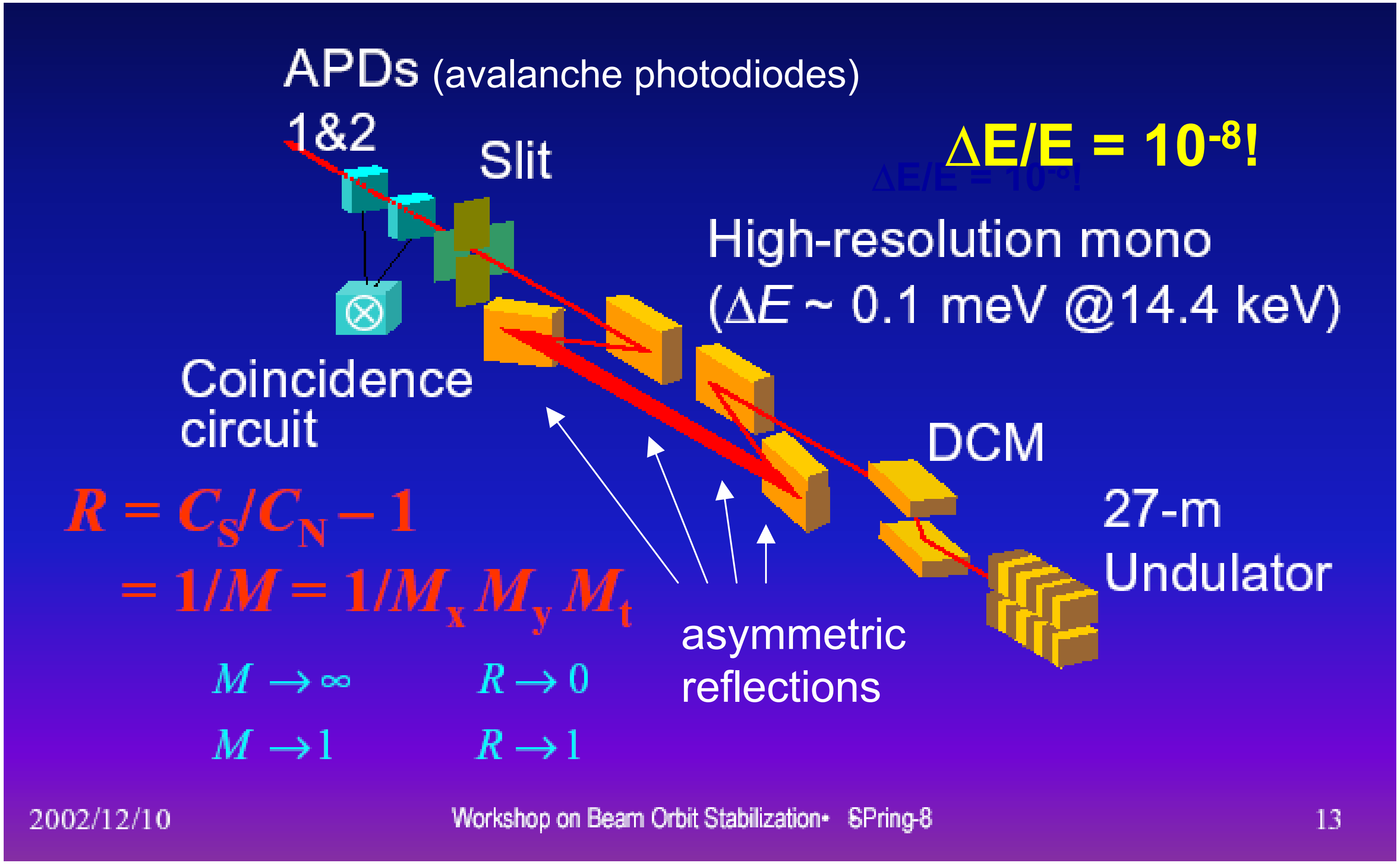
$$l_{coh} = \lambda_{ph}(\lambda/\Delta\lambda)_{mono} = \sim 20\ \mu\text{m for } 2\ \text{Å photons}$$

SR requirements:

intensity stability at sample: **~10^{-3}**

X-ray Intensity Interferometry

T. Ishikawa



Hambury Brown-Twiss Interferometer at SPring-8

Photon Beam Stability Specifications – Storage Rings

General stability requirements:

- intensity after apertures — **< 0.1%**
  apertures in phase space — **(~.01% for dichroism)**
- steering accuracy on small samples — **< few % photon beam size**
- e- trajectory in IDs — **< few % electron beam size**
  emission pattern, off-axis energy pattern, switched polarization, etc.
- photon energy — **10^{-4} resolution**
  ($<10^{-5}$ for some[a])
- timing — **< 10% critical time scale**
  pump-probe, etc.
- beam lifetime — **many hours**
  (unless have top-off injection)

[a] R. Follath and F. Senz, Synchrotron Radiation News 12, 34 (1999)

Photon Beam Stability Specifications – cont.

Stability requirements depend on:

- photon beam properties

  dependent on electron beam properties

- experiment sample properties

  e.g. size, mosaicity, concentration, etc.

  phase space acceptance

- beam line optical components, apertures, etc.
- time scale

Experiment Sensitivity to Electron Beam Parameters

Response of experiment observable parameters to source point electron beam parameters: sensitivity matrix M(i,j)

$$[\Delta P_{exp}(i)] = \mathbf{[M(i,j)]}\ [\Delta P_{e-}(j)]$$

where

$$[\Delta P_{exp}(i)] = \begin{pmatrix} \Delta I_{ph} \\ \Delta E_{ph} \\ \Delta E_{ph}/E_{ph}\ (\mathrm{rms}) \\ \Delta\sigma_x \\ \Delta\sigma_y \\ \Delta\sigma'_x \\ \Delta\sigma'_y \\ \Delta\sigma_z \\ \Delta x \\ \Delta y \\ \Delta x' \\ \Delta y' \\ \Delta t_{bunch} \\ \text{polarization} \\ \text{coherence} \end{pmatrix} \qquad [\Delta P_{e-}(i)] = \begin{pmatrix} \Delta I_{e-} \\ \Delta E_{e-} \\ \Delta E_{e-}/E_{e-}\ (\mathrm{rms}) \\ \Delta\sigma_x \\ \Delta\sigma_y \\ \Delta\sigma_z \\ \Delta\sigma'_y \\ \Delta\sigma_z \\ \Delta\theta_{rot} \\ \Delta x \\ \Delta y \\ \Delta x' \\ \Delta y' \\ \Delta t\ _{bunch} \end{pmatrix}$$

User observable - electron observable sensitivity matrix

M. Green, Aladdin

Requirement	User Observables	Electron Beam Observables								
		x	y	x'	y'	θ_z (coupling)	σ_x	σ_y	δz, δt	$\delta\epsilon$
	Throughput									
	Energy									
	Shift									
	Spread									
	Image									
	x									
	y									
	σ_x									
	σ_y									
	Timing									
	Polarization									

Stability Relationships

Can derive basic some basic relationships experimental observables and beam properties based simple (1st-order) dependencies:

experiment parameters	beam orbit	beam size	beam energy/ energy spread
intensity	x	x	x
energy resolution	x		x
timing, bunch length		x	x

Electron Beam Properties

Electron beam characterized by conjugate variable pairs in 6-D phase space:

x, x′ y, y′ E, t (or ϕ)

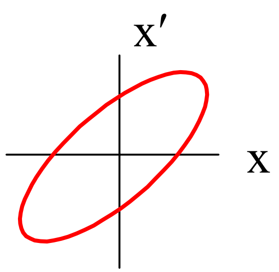
-------- transverse ---------- **longitudinal**

For each conjugate pair, beam occupies phase space ellipse of constant area - or emittance (A = $\pi\varepsilon$)

transverse: $$\varepsilon_x = \gamma(s)x^2 + 2\alpha(s)xx' + \beta(s)x'^2 = \text{cons tan t}$$

$$\alpha = -\beta'/2 \qquad \gamma = \frac{1+\alpha^2}{\beta}$$

$$\varepsilon_y \cong k\varepsilon \qquad (k = \text{coupling},\ k <\sim 0.1)$$



e- beam size: $$\sigma_x(s) = \sqrt{\varepsilon_x\beta_x(s) + (\eta(s)\delta)^2} \qquad \sigma_y(s) = \sqrt{\varepsilon_y\beta_y(s)} \qquad \delta = \Delta E/E$$

e- divergence: $$\sigma'_x(s) = \sqrt{\varepsilon_x\gamma_x(s) + (\eta'(s)\delta)^2} \qquad \sigma'_y(s) = \sqrt{\varepsilon_y\gamma_y(s)}$$

Electron Beam Properties – cont.

Longitudinal parameters:

emittance: $$\varepsilon_s = \int_s \frac{\Delta E}{\omega_{rf}} d\phi = \sigma_s \sigma_\delta \qquad \delta = \Delta E / E$$

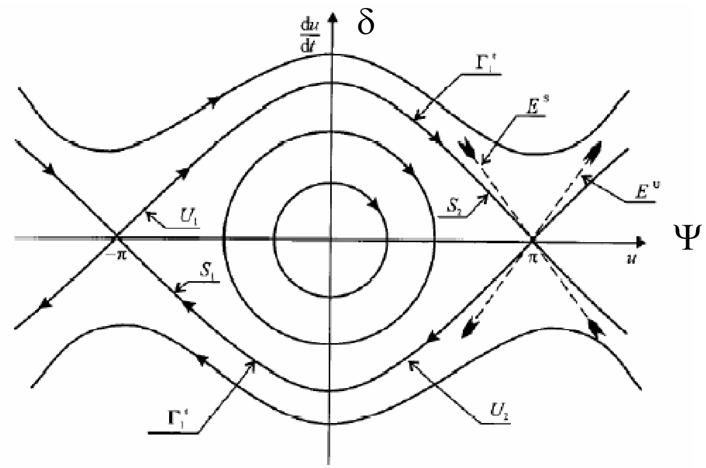
$$\delta = \delta_{max} \sin \Omega_s t$$

$$\delta_{max} = \frac{\Omega_s}{\alpha_c \omega_{rf}} \phi_{max} = \frac{\nu_s}{\alpha_c h} \phi_{max}$$

synchrotron frequency: $$\Omega_s = \sqrt{\frac{\alpha_c \omega_{rf} e V_{rf}^0 \cos \phi_s}{E_0 T_0}}$$

bunch length (m): $$\sigma_s = \frac{\alpha_c c}{\Omega_s} \sigma_\delta$$

bunch length (s): $$\sigma_t = \frac{\alpha_c}{\Omega_s} \sigma_\delta$$



Phase-space portrait of a pendulum

Kapitaniak, T. Chaos for engineers : theory, applications, and control. Springer Verlag, 1998

α_c = momentum compaction factor | ν_s = synchrotron tune | h = harmonic #

ϕ_s = synchronous phase | $T_0 = 2\pi h/\omega_{rf}$ = rev period | V_{rf}^0 = peak rf voltage

Electron Beam Properties – cont.

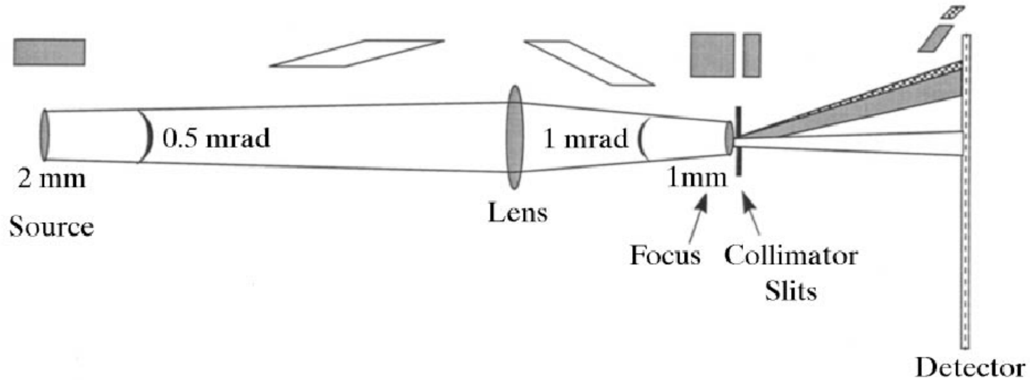
Have coupling between phase space planes:

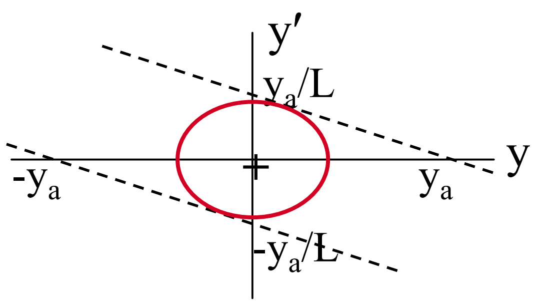
- H-V by skew quads, orbit in sextupoles, resonances
- transverse-longitudinal (Touschek scattering, $\Delta x = \eta \Delta E/E$)
- photon energy dependent on orbit through IDs
- photon polarization dependent on vertical orbit through dipole
- etc.

Experiment in Phase Space

Can represent experiment configuration in phase space

C. Nave





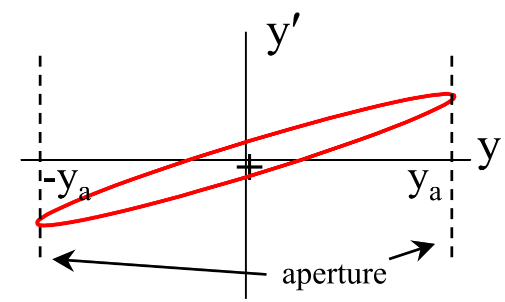
source point

$$\xleftarrow{-L}$$

$$y_{exp} = y_{sp} + L y'_{sp}$$
$$y'_{exp} = y'_{sp}$$

$$\xrightarrow{L}$$

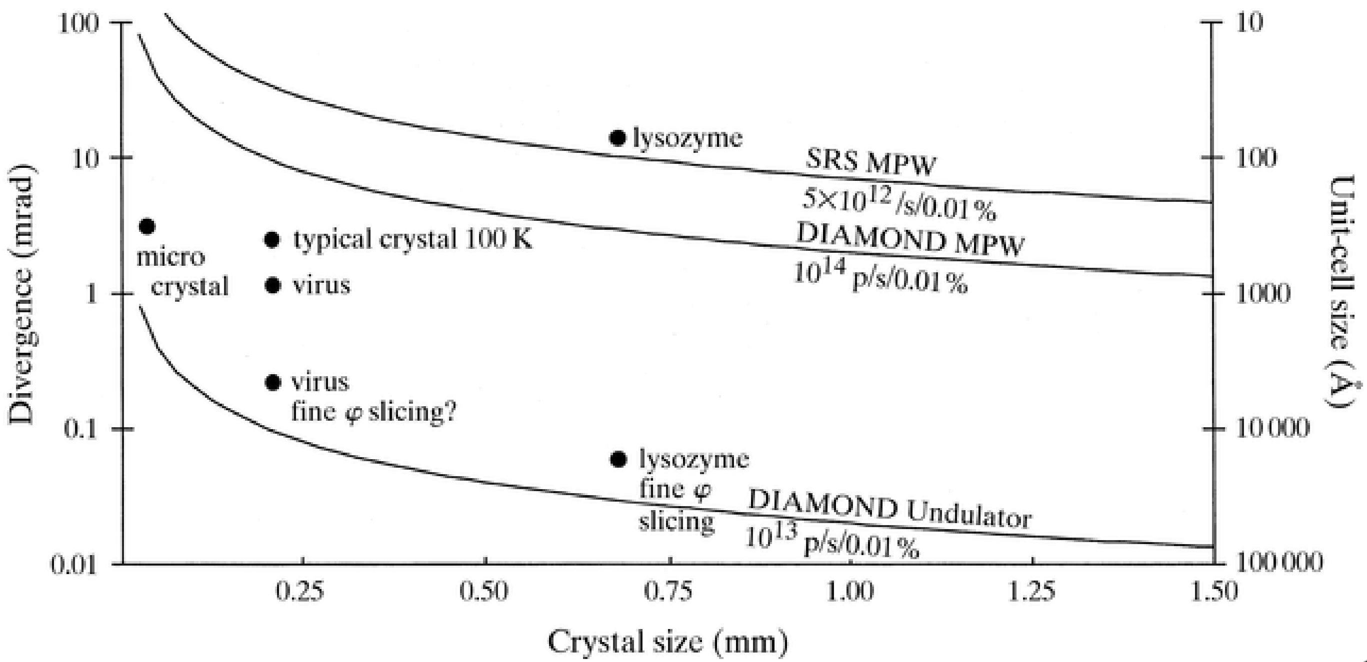
$$\begin{pmatrix} y \\ y' \end{pmatrix}_{s_1+L} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} y \\ y' \end{pmatrix}_{s_1}$$



experiment

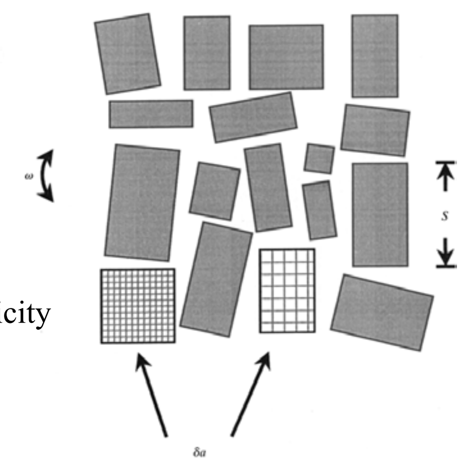
Can propagate beam phase space through beam line with transport matrices representing drifts, reflections, focusing, etc. **– ray tracing programs**

Crystal Acceptance in Phase Space



C. Nave

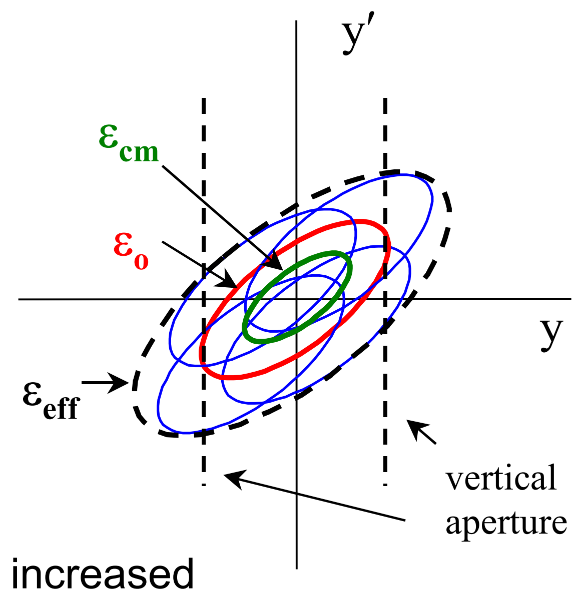
mosaicity



Stability in Phase Space

Goal for accelerator people:

Stabilize electron motion in 6-D phase space with respect to apertures



For disturbance periods << experiment integration time:

$$\varepsilon = \varepsilon_o + \varepsilon_{cm} \qquad \Delta\varepsilon/\varepsilon = \varepsilon_{cm}/\varepsilon_o$$

(assuming aligned ellipses)

Note: for frequencies >> integration time, will refer to an increased spread in parameter value due to disturbance as **rms spread**

For disturbance periods < experiment integration time:

$$\varepsilon\ (\text{envelope}) = \varepsilon_o + 2(\varepsilon_o\,\varepsilon_{cm})^{1/2} + \varepsilon_{cm} \qquad \Delta\varepsilon/\varepsilon \cong 2\,(\varepsilon_{cm}/\varepsilon_o)^{1/2}$$

(for $\varepsilon_{cm} << \varepsilon_o$; L. Farvacque, ESRF)

Note: for frequencies < integration time, will refer to a shift in parameter value (e.g. Δy) as a **coherent shift**

Can apply similar analysis to other phase space dimensions

Beam Stability Time Scales

- **Disturbance periods << experiment integration time:**

  Orbit disturbances blow up effective beam σ and σ', reduce intensity at experiment, but do not add noise

  For $\Delta\varepsilon/\varepsilon = \varepsilon_{cm}/\varepsilon_o < \sim 10\%$: **$\Delta y_{cm}$(rms) < ~0.3 σ_y** **$\Delta y'_{cm}$(rms) < ~0.3 $\sigma_{y'}$**

  Note: can have frequency aliasing if don't obey Nyquist….

- **Disturbance periods $\geq$ experiment integration time:**

  Orbit disturbances add noise to experiment

  For $\Delta\varepsilon/\varepsilon = \sim 2\sqrt{\varepsilon_{cm}/\varepsilon_o} < \sim 10\%$: **$\Delta y_{cm}$(rms) < 0.05 σ_y** **$\Delta y'_{cm}$(rms) < 0.05 $\sigma_{y'}$**

- **Disturbance periods >> experiment time (day(s) or more):**

  Realigning experiment apparatus is a possibility

- **Sudden beam jumps or spikes can be bad even if rms remains low**

  Peak amplitudes can be **> x5** rms level

Beam Stability Time Scales – cont.

Most demanding stability requirements:

- Orbit disturbance frequencies approximately bounded at high end by data sampling rate and a low end by data integration and scan times

$\Rightarrow$ **noise not filtered out**

Data acquisition time scales:

- Most experiments average for 100 ms or more
- Some experiments average over much shorter times (e.g. 100 kHz)

$\Rightarrow$ **sensitive to synchrotron oscillations (~10 kHz)**

- Acquisition rates are increasing, averaging times decreasing

MHz for turn-turn measurements

single-shot acquisition for pulsed sources (e.g. linac FELs)

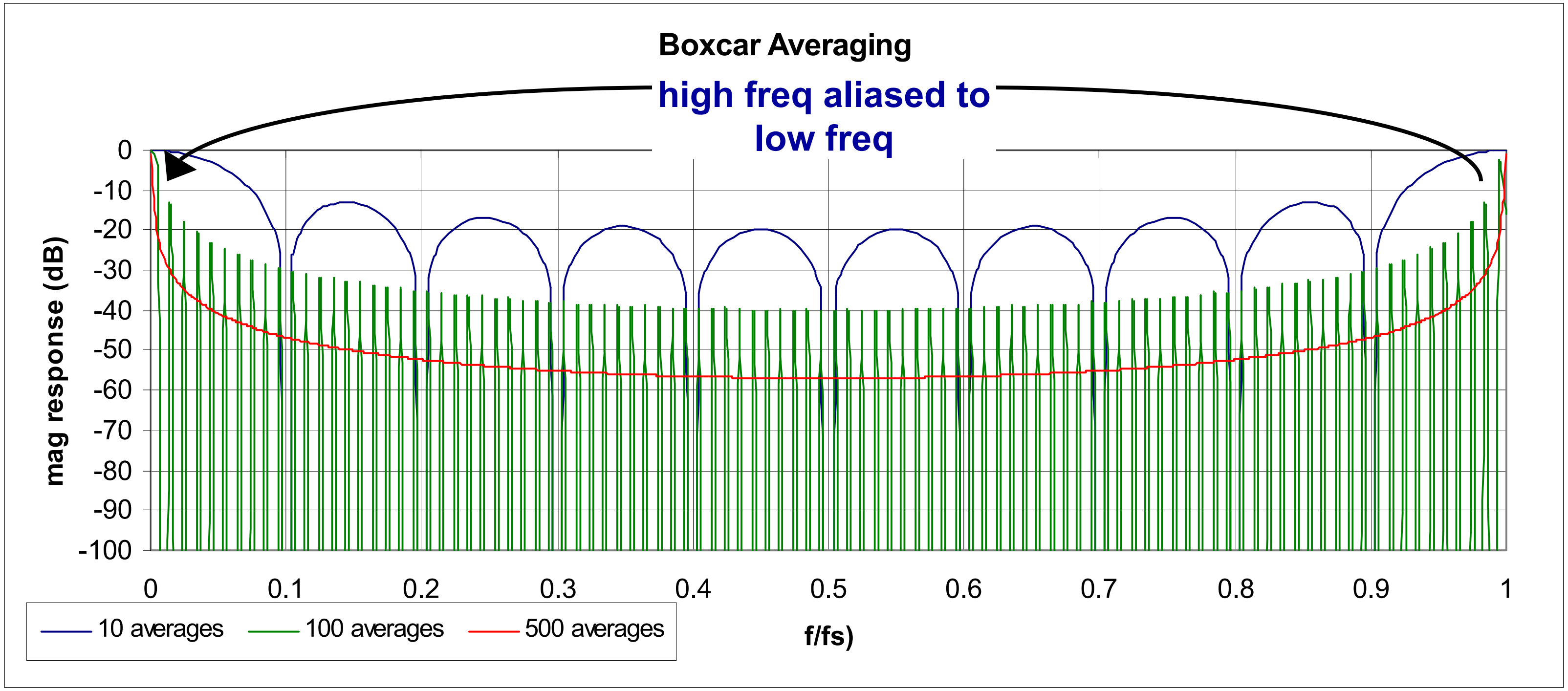
Data Averaging

Boxcar averaging:

take average of M data sets

$$H(f) = \frac{\sin(\pi M f / f_s)}{M \sin(\pi f / f_s)}$$

f_s = data sampling frequency

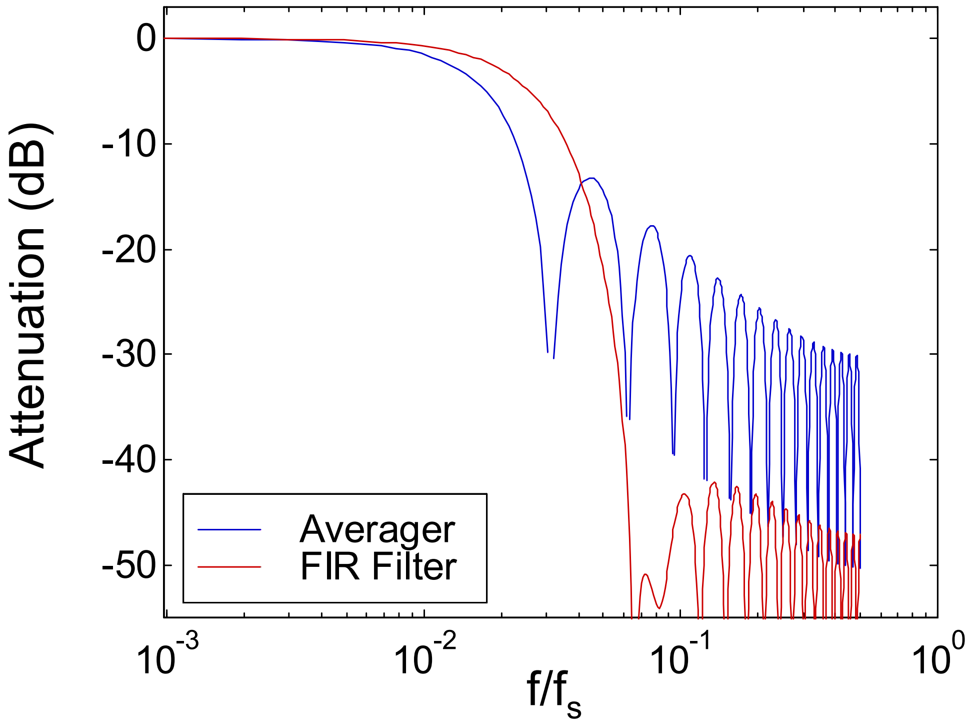


averaged data could be corrupted by aliaising of higher frequencies

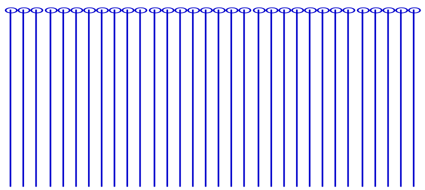
Data Averaging - cont

FIR filter: finite impulse response filter is a better way to average M samples

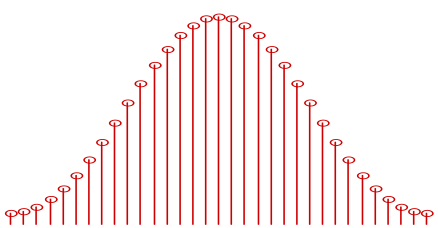
32 averages vs. 32-tap FIR



Averager Coefficients

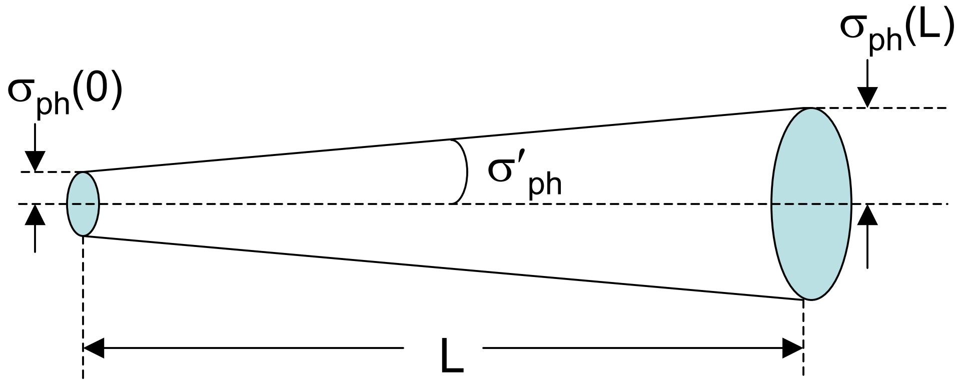


FIR Filter Coefficients



Photon-Electron Relationships

Photon beam size:



- unfocused, vertical plane:

  (assume depth of field = 0)

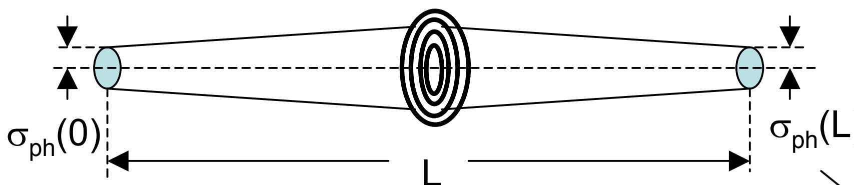
  $\sigma_{ph}(L) = [\sigma_{ph}(0)^2 + L^2\sigma_{ph}'^2]^{1/2}$

  $\sigma_{ph}(0) = [\sigma_{e-}{}^2 + \sigma_{diff}{}^2(\lambda)]^{1/2}$

  i.e the convolution of electron beam size and diffraction-limited apparent size of a single electron (quadrature sum of 2 Gaussian distributions).

$$\sigma_{\text{diff}} = \frac{\lambda}{4\pi\sigma'_{\Psi}(\lambda)}$$

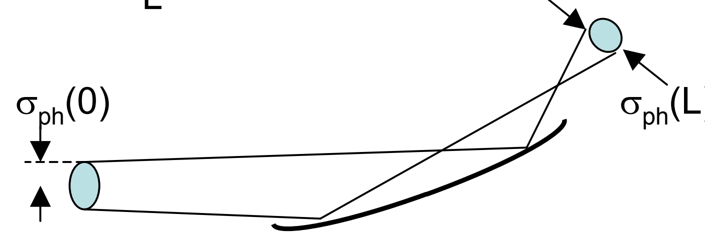
$\sigma_{e-} = [\varepsilon\beta(s) + (\eta(s)\delta)^2]^{1/2}$



- focused (1:m, m = magnification):

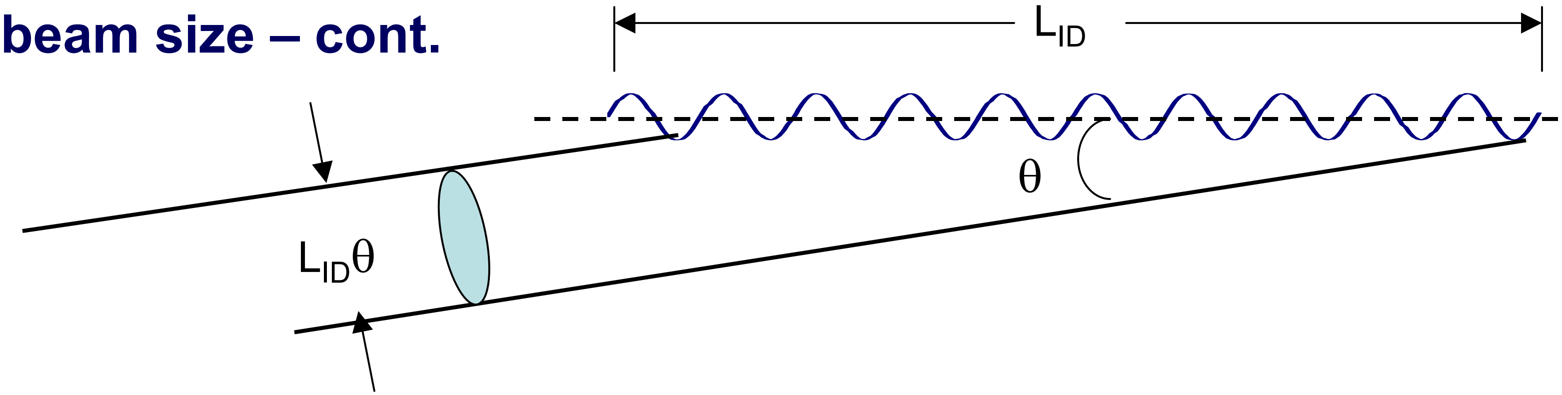
  $\sigma_{ph}(L) = m\sigma_{ph}(0)$ **(~insensitive to angle)**

  $\sigma'_{ph}(L) = -\sigma'_{ph}(0)/m$



Photon-Electron Relationships – cont.

Photon beam size – cont.



- Off-axis view of ID radiation adds to focused beam size due to extended source
- On-axis beam size has additional terms arising from wiggle amplitude and ID length:

$$\sigma_{Tx}^2 = \sigma_r^2 + \sigma_x^2 + a^2 + \tfrac{1}{12}\sigma_{x'}^2 L^2 + \tfrac{1}{36}\varphi^2 L^2 \qquad \sigma_{Tx'}^2 = \sigma_{r'}^2 + \sigma_{x'}^2$$

from I.V.Bazarov

$$\sigma_{Ty}^2 = \sigma_r^2 + \sigma_y^2 + \tfrac{1}{12}\sigma_{y'}^2 L^2 + \tfrac{1}{36}\psi^2 L^2 \qquad \sigma_{Ty'}^2 = \sigma_{r'}^2 + \sigma_{y'}^2$$

- DIpole source size is slightly increased from finite depth of field and orbit arc

Photon-Electron Relationships – cont.

Photon beam divergence:

$$\sigma'_{ph}(L) = \sigma'_{ph}(0) = [\sigma'^{2}_{e-} + \sigma'^{2}_{\Psi}]^{1/2}$$

$$\sigma'_{e-} = [\varepsilon\gamma(s) + (\eta'\delta)^2]^{1/2}$$

for dipoles and wigglers:

$$\sigma'_{\psi}(\lambda) \cong \begin{cases} \dfrac{1.07}{\gamma}\left(\dfrac{\lambda}{\lambda_c}\right)^{1/3} & \lambda \gg \lambda_c \\[2ex] \dfrac{0.64}{\gamma} & \lambda = \lambda_c. \\[2ex] \dfrac{0.58}{\gamma}\left(\dfrac{\lambda}{\lambda_c}\right)^{1/2} & \lambda \ll \lambda_c \end{cases}$$

$$\lambda_c = \frac{2\pi c}{\omega_c} = \frac{hc}{E_c} \qquad h = \text{Planck's const.}$$
$= 4.14 \times 10^{-18}$ keV-s

$$E_c(\text{keV}) = \frac{3\hbar c\gamma^3}{2\rho} = 0.665\,B(T)\,E^2(\text{GeV})$$

for planar undulators:

(on-axis, central cone)

$$\sigma'_{\Psi}(n) = \sqrt{\frac{\lambda_n}{L_u}} = \frac{1}{\gamma}\left[\frac{\lambda_u(1+K^2/2)}{2nL_u}\right]^{1/2} = \frac{1}{\gamma}\left[\frac{1+K^2/2}{2nN_u}\right]^{1/2}$$

n = harmonic # L_u = undulator length λ_u = undulator period N_u = # periods K = ~1

Photon-Electron Relationships – cont.

Typical photon beam dimensions

3 GeV 3rd generation source with ε = ~10 nm-rad, 1% coupling, E_c = 7.5 keV:

	dipole/wiggler		undulator (N=100, n=1, E_1 = 2 keV)	
	hor	vert	hor	vert
σ_{e-} (μm)	100-500	20-50	100-500	20-50
σ'_e (μrad)	20-100	2-5	20-100	2-5
σ_{diff} (E_c) (μm)	0.12	0.12	3.6	3.6
σ'_ψ (E_c) (μrad)	107	107	14	14
σ_{ph} (E_c) (μm)	**100-500**	**20-50**	**100-500**	**20.3-50.1**
σ'_{ph} (E_c) (μrad)	**mrads**	**107**	**24-101**	**14.1-14.9**

For 100-period undulator, n = 5 (~10 keV), **σ'_{ph} (n = 5) = 6.6 – 8 μrad**

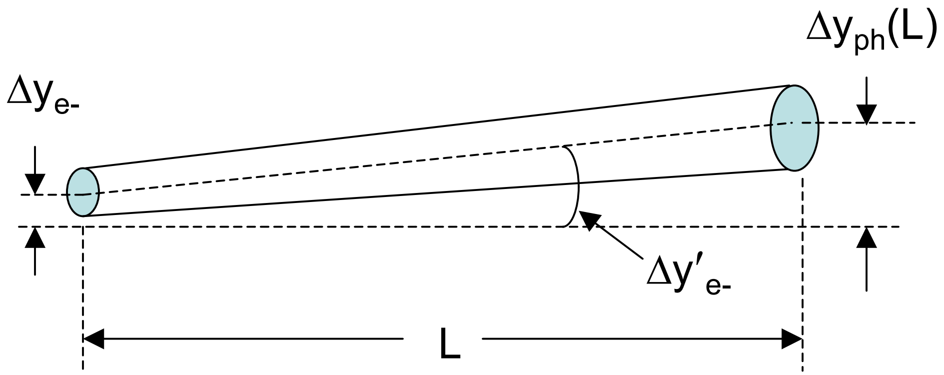
Photon-Electron Relationships – cont.

Beam line steering:

- pointing parameters (1st order) for **unfocused** photon centroid:

$$\Delta y_{ph}(L) = \Delta y_{e-} + L\Delta y'_{e-}$$

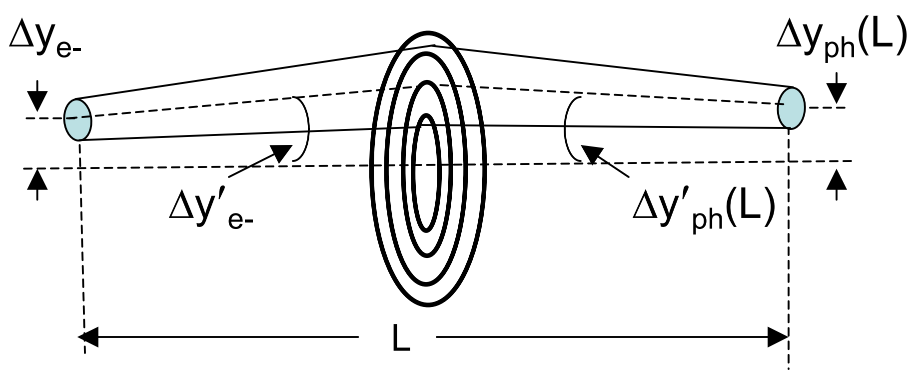
$$\Delta y'_{ph}(L) = \Delta y'_{e-}$$



- **focused** (1:m) photon centroid:

$$\Delta y_{ph}(L) = m\Delta y_{e-}$$

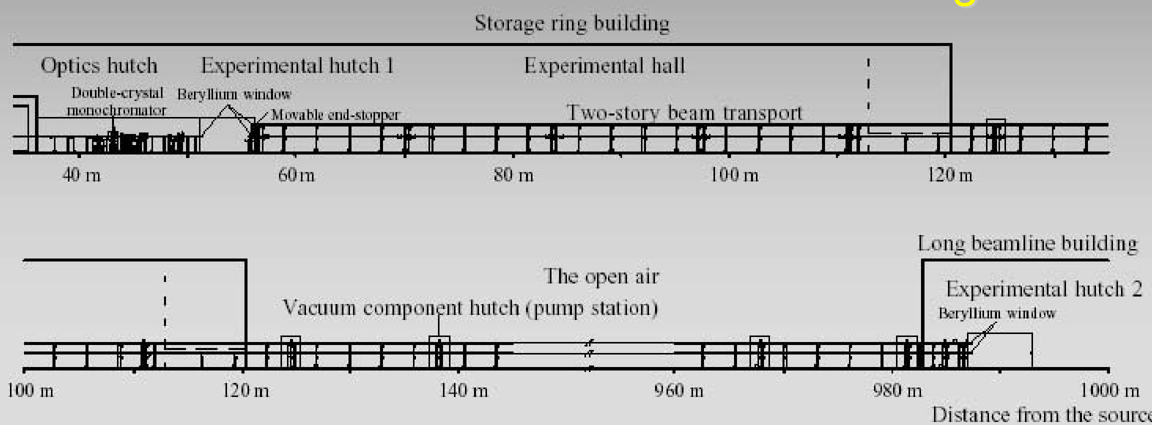
$$\Delta y'_{ph}(L) = -\Delta y'_{e-}/m$$



L is large in some cases…..

1000 m Beamline, BL29XU

SPring-8



Ishikawa *et al. Proc. SPIE* (2001)

Photon-Electron Relationships – Photon Energy

Dipole critical energy:

$$E_{crit\,dip}(\mathrm{keV}) = \frac{h}{2\pi}\,\omega_c = 0.665B(\mathrm{T})E_{e-}^{\;2}(\mathrm{GeV})$$

Wiggler critical energy:

$$E_{crit\,wigg}(\theta) = E_{crit\,dip}\left[1-\left(\frac{\theta\gamma}{K}\right)^2\right]^{1/2}$$

where θ is horizontal viewing angle,

$K = \delta/\gamma^{-1}$, ratio of wiggler deflection angle δ to beam opening angle

Undulator harmonics:

$$E_n(\mathrm{keV}) = 0.95\frac{nE_{e-}^{\;2}(\mathrm{GeV})}{\lambda_u(\mathrm{cm})}\left(\frac{1}{1+K^2/2+(\gamma\theta)^2}\right) \qquad \frac{\Delta E_n}{E_n} = \frac{1}{nN_u}$$

n = harmonic number λ_u = undulator period N_u = # periods θ = hor or vert view angle

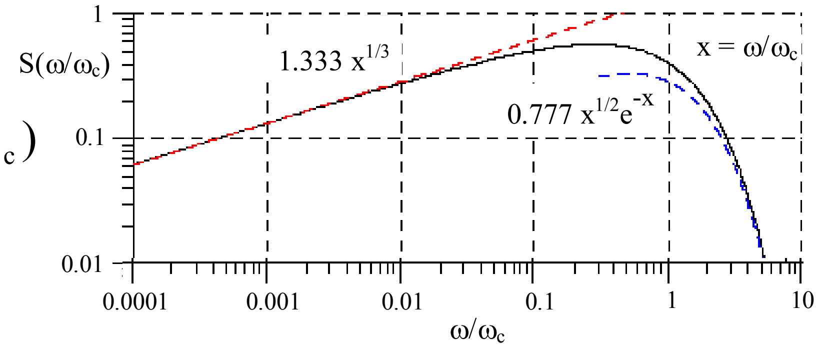
for zero-emittance, zero-energy-spread electron beam

Photon-Electron Relationships – Photon Emission

K-J Kim

Dipole spectral flux density (per horizontal mrad, integrated over vertical angle):

$$\frac{dF_{dip}(\omega)}{d\theta} = 2.457 \times 10^{16} \frac{\Delta\omega}{\omega} E_{e-}^{2}(\text{GeV})\, I(\text{A})\, S(\omega/\omega_c)$$



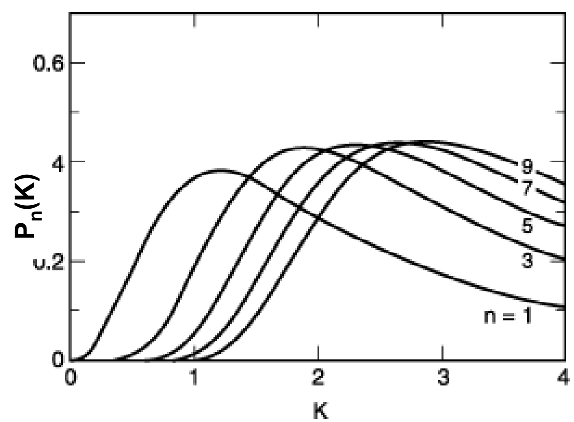
Wiggler spectral flux density:

$$\frac{dF_{wigg}(\omega)}{d\theta} =\sim N_{wigg} \frac{dF_{dip}(\omega)}{d\theta} \qquad N_{wigg} = \#\,\text{wiggler poles}$$

Undulator spectral flux density:

$$\left.\frac{d^2F_{und}(\omega_n)}{d\theta\, d\varphi}\right|_{\varphi,\theta=0} = 1.744 \times 10^{14} \frac{\Delta\omega}{\omega} N_u^{2} E_{e-}^{2}(\text{GeV})\, I(\text{A})\, P_n(K)$$

N_u = # undulator periods



Undulator Radiation

Angular distribution of 1st harmonic:

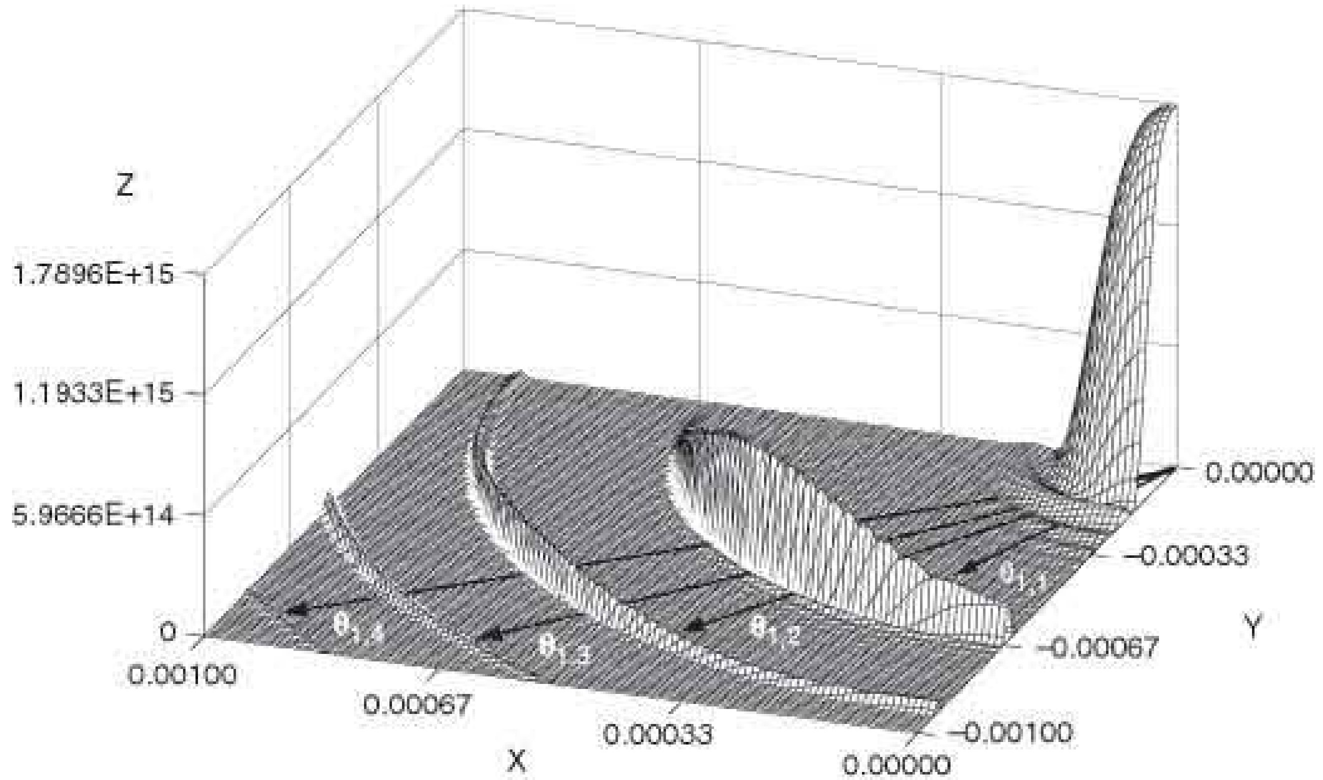


Fig. 2-5. *The angular distribution of fundamental (n = 1) undulator radiation for the limiting case of zero beam emittance. The x and y axes correspond to the observation angles θ and ψ (in radians), respectively, and the z axis is the intensity in photons·s^{-1}·A^{-1}·$(0.1\ mr)^{-2}$·$(1\%\ bandwidth)^{-1}$. The undulator parameters for this theoretical calculation were N = 14, K = 1.87, λ_u = 3.5 cm, and E = 1.3 GeV. (Figure courtesy of R. Tatchyn, Stanford University.)*

K-J Kim, from X-ray Data Booklet, LBNL

Undulator Radiation – an aside (from K-J Kim)

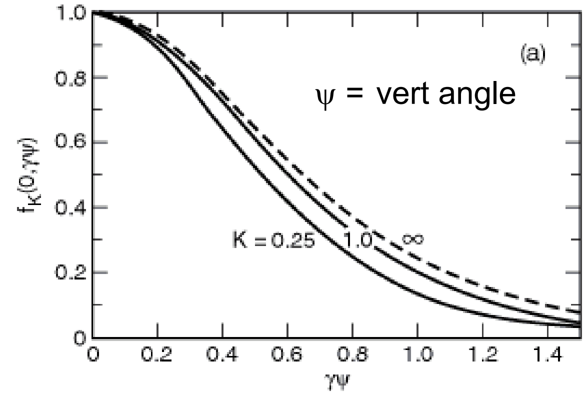
Total radiated power from undulator or wiggler:

$$P_T = \frac{N}{6} Z_0 I e \frac{2\pi c}{\lambda_u} \gamma^2 K^2 \qquad Z_0 = 377\ \Omega$$

$$P_T(\mathrm{kW}) = 0.633 E^2(\mathrm{GeV}) I(\mathrm{A}) B_0^2(\mathrm{T}) L_u(\mathrm{m})$$

$$P_T(\mathrm{W}) = 7.26 E^2(\mathrm{GeV}) I(\mathrm{A}) N_u K^2 / \lambda_u(\mathrm{cm})$$

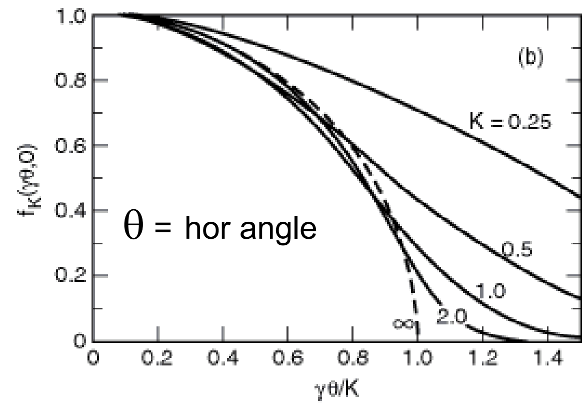
For K = 0.1, λ_u = 3.3 cm, B_0 = 0.03T, E = 7 GeV,
L_u = 70 x 3.3 cm = 2.31 m, I = 0.1 A, **P_T = ~7.5 W**



Angular distribution of power:

$$\frac{d^2P}{d\theta d\psi}(\mathrm{W/mrad}^2) = 10.84\, B_0(\mathrm{T}) E^4(\mathrm{GeV})\, I(\mathrm{A})\, N_u G(K)\ f_K(\gamma\theta, \gamma\psi)$$

= **~550 W/mrad²** on axis (ψ = θ = 0)

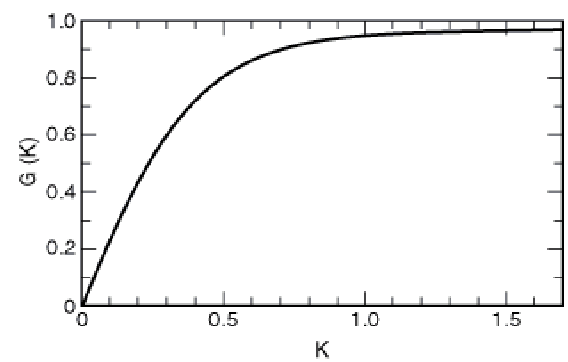


Photon divergence:

$$\sigma'_\Psi(n) == \frac{1}{\gamma}\left[\frac{1+K^2/2}{2nN_u}\right]^{1/2} = 6\ \mu\mathrm{rad}, \quad \gamma\psi = 0.085$$

for N = 70, E = 7GeV, K = 0.1, n=1

But horizontal σ'_{e-} = ~20 μrad ⇒ σ'_{tot} = ~21 μrad ⇒ γθK = 0.029

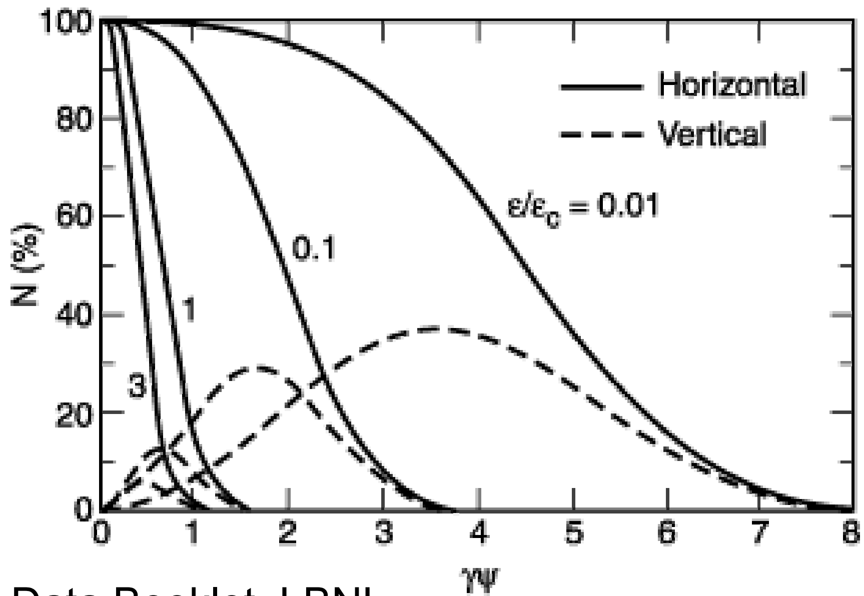


Photon-Electron Relationships - Polarization

- SR from dipole is linearly polarized in horizontal plane when viewed in this plane
- Polarization is elliptical when viewed out of horizontal plane

  rotation sense reverses as vertical angle changes from positive to negative

- Elliptical polarization can be decomposed into horizontal and vertical components:



K-J Kim, from X-ray Data Booklet, LBNL

Intensity Stability

Want high level of flux (F) constancy through aperture or steering accuracy to hit small sample **(sample size on order of beam size σ)**

$\Delta F/F < 10^{-3}$ (typical)

Note: some experiments require **$< 10^{-4}$** flux constancy

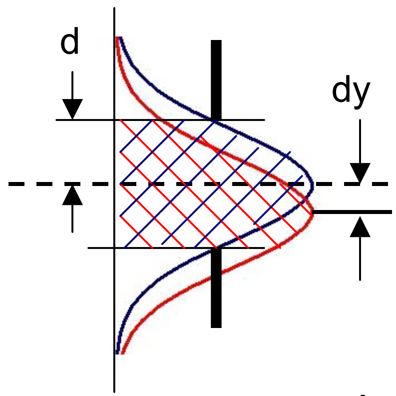
e.g. **photoemission electron spectroscopy combined with dichroism spectroscopy (subtractive processing of switched polarized beam signals)**

Flux variations caused by

- orbit instability
- beam size instability
- energy instability

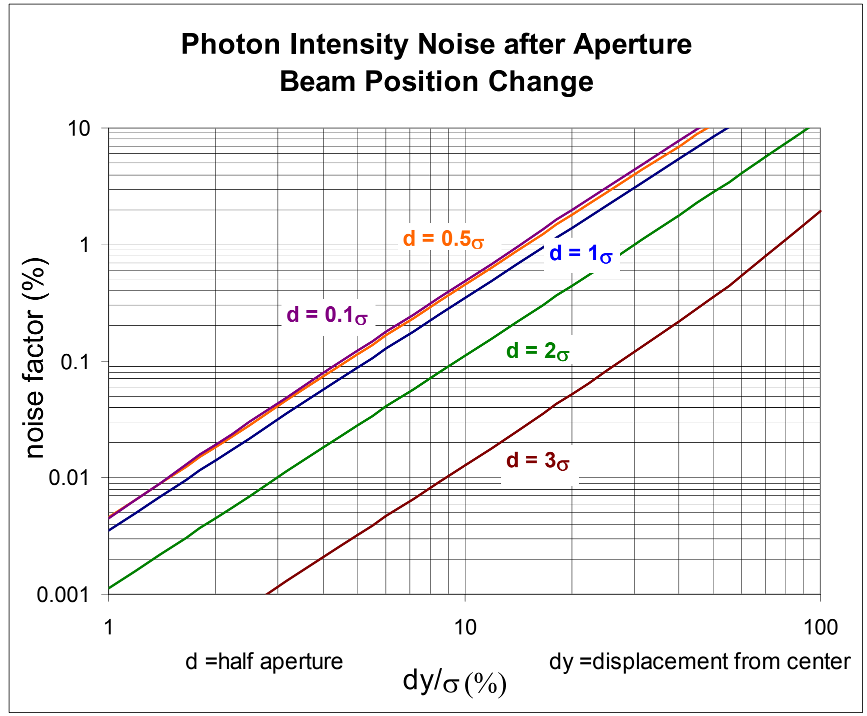
Intensity Stability after Apertures

Sensitivity of intensity (flux) to beam position change:



$$F_{y=0} = \frac{F_{tot}}{\sqrt{2\pi}\sigma_y} \int_{-d}^{d} e^{\frac{-y^2}{2\sigma_y^2}} dy$$

$$F_{y=dy} = \frac{F_{tot}}{\sqrt{2\pi}\sigma_y} \int_{-d}^{d} e^{\frac{-(y-dy)^2}{2\sigma_y^2}} dy$$



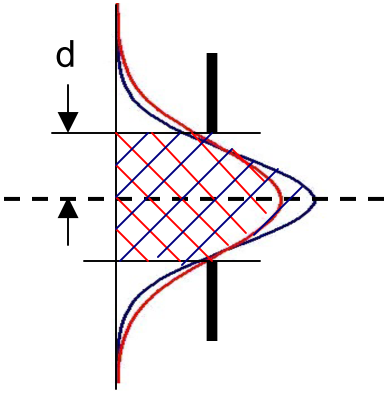
F_{tot} = total flux in Gaussian beam before aperture

"noise factor" = $|F_0 - F_{dy}|/F_0$ **~ dy^2**

For noise factor (intensity stability) <0.1%, **dy < 5% σ_y** **(<1.5% σ_y for 0.01% stability)**

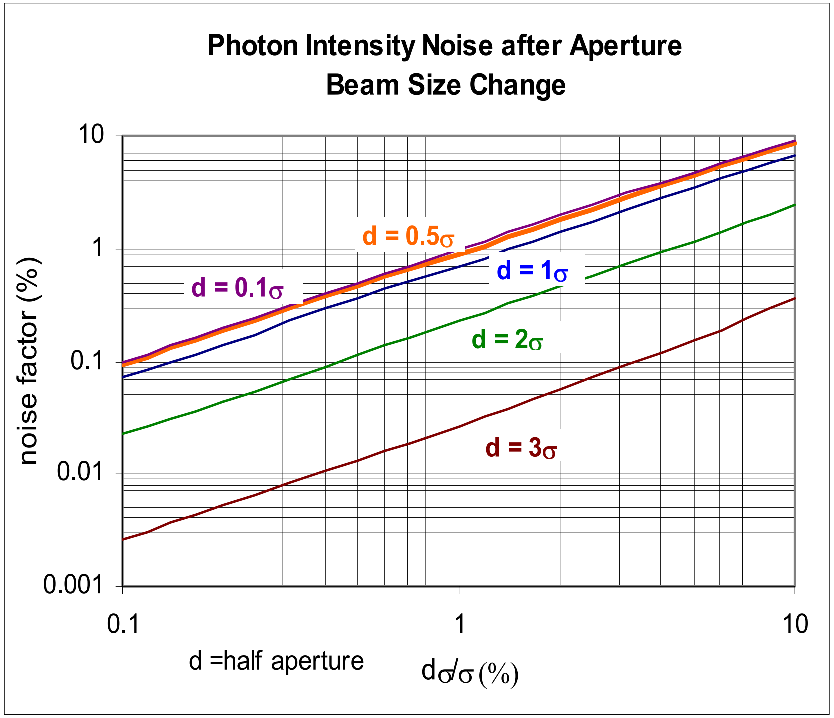
Intensity Stability after Apertures - cont.

Sensitivity of intensity (flux) to beam size change:



$$F_{\sigma_0} = \frac{F_{tot}}{\sqrt{2\pi}\sigma_0} \int_{-d}^{d} e^{\frac{-y^2}{2\sigma_0{}^2}} dy$$

$$F_{\sigma_0+d\sigma} = \frac{F_{tot}}{\sqrt{2\pi}(\sigma_0 + d\sigma)} \int_{-d}^{d} e^{\frac{-y^2}{2(\sigma_0+d\sigma)^2}} dy$$



noise factor = $|F_{\sigma 0}-F_{\sigma 0+d\sigma}|/F_{\sigma 0}$ **~ dσ**

For noise factor (intensity stability) <0.1%, **dσ < 0.1% σ_y**

(<0.01% σ_y for 0.01% stability)

Intensity Stability Sensitivities

Orbit

- Steering to small apertures:

For <0.1% intensity stability, beam position at small apertures or small sample sizes should be **<5%** σ

unfocused photon centroid: $\Delta y_{ph}(L) = \Delta y_{e-} + L\Delta y'_{e-}$ $\Delta y'_{ph}(L) = \Delta y'_{e-}$

$\Rightarrow$ beam position dominated by angle $\Rightarrow$ $\boldsymbol{\Delta y'_{e-} < 5\%\ \sigma'_y}$

< ~100s μrad hor. in dipole **< 5 μrad vertical for dipole/wiggler**

< 1-5 μrad hor. in undulator **< 0.7 μrad vertical for undulator**

for 3rd gen 3 GeV, ε = ~10 nm-rad

focused (1:m) photon centroid: $\Delta y_{ph}(L) = m\Delta y_{e-}$ $\Delta y'_{ph}(L) = -\Delta y'_{e-}/m$

$\Rightarrow$ beam position dominated by source position $\Rightarrow$ $\boldsymbol{\Delta y_{e-} < 5\%\ \sigma_y}$

< 5-25 μm horizontal, < 1-2.5 μm vertical for 3rd gen

Intensity Stability Sensitivities - cont.

Orbit - cont.

- Orbit through **wigglers:**

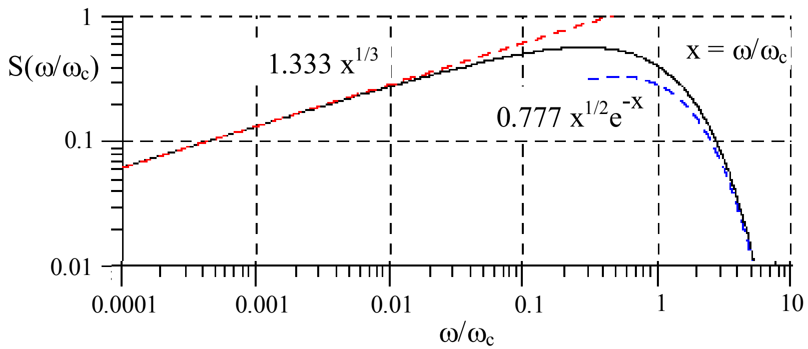
Wiggler critical energy depends on horizontal view angle θ:

$$E_{\text{crit wigg}}(\theta) = E_{\text{crit dip}}\left[1 - \left(\frac{\theta\gamma}{K}\right)^2\right]^{1/2}$$

$K = \delta/\gamma^{-1}$, δ = wiggler deflection

Change in orbit angle $\Delta\theta_x$ through wiggler causes intensity change due to change in E_{crit} and dependence of spectral flux per mrad $F_{wigg}(\omega)$ on E_{crit}:

$$\frac{dF_{wigg}(\omega)}{d\theta} \propto E_{e-}^2 S(\omega/\omega_c)$$



Let $H(\omega) = dFwigg(\omega)/d\theta$. Then

$$\frac{dH(\omega)}{d\theta} = \frac{dH(\omega)}{dS(\omega/\omega_c)}\,\frac{dS(\omega/\omega_c)}{d(\omega/\omega_c)}\,\frac{d(\omega/\omega_c)}{d\omega_c}\,\frac{d\omega_c}{d\theta}$$

For **ω = ~3ωc** , K = 40, θ = 3.5 mrad (side station):

dH/H =~0.1% $\Rightarrow$ **$\Delta\theta_x$ = ~5 μrad** (for zero-emittance beam)

Intensity Stability Sensitivities - cont.

Beam Size

- For 0.1% intensity stability, beam size stability should be **$\Delta\sigma/\sigma$ < ~10^{-3}**
- Beam size-perturbing mechanisms:
  - changes in horizontal-vertical electron beam coupling

    ID gap change, orbit in sextupoles, energy ramp without coupling correction

  - collective effects

    coupling resonances, single- and multibunch instabilities in transverse and longitudinal planes, intrabeam scattering

  - gas bursts, ions, dust particles
  - electron energy variations in lattice dispersion sections at frequencies > data integration time

    synchrotron oscillations, Landau damping mechanisms, etc.

Intensity Stability Sensitivities- cont.

Energy

- Energy-dependent orbit:

$$\Delta x(s) = \eta_s \delta_{e-} < .05\sigma_x \qquad \Delta x'(s) = \eta_s' \delta_{e-} < .05\sigma_x \qquad \delta_{e-} = \frac{\Delta E_{e-}}{E_{e-}}$$

At dispersion source points (i.e. dipoles), $\eta_x \sim 0.1\text{-}0.5$ m, $\eta'_x \sim 0.1\text{-}0.5$ ($\eta_y \sim 0.02$ m).

For $\Delta x = \eta \, \Delta E/E < .05\sigma_x = \sim 10\text{-}20\ \mu\text{m}$,

ΔE/E (coherent) < 10^{-4} - 10^{-5}

$\Rightarrow$ phase oscillation amplitude **ϕ <~0.01° - 0.1°** ($\phi_{max} = \frac{\alpha_c h}{\nu_s} \delta_{max}$, α = .001, ν = .01, h = ~360)

and rf frequency stability **$\Delta f_{rf}/f_{rf}$ < ~10^{-7} - 10^{-8}** ($\Delta f_{rf}/f_{rf} = \alpha_c \Delta E/E$)

$\Rightarrow$ Δf_{RF} **< 5 - 50 Hz** for f_{RF} = 500 MHz

imposes limit on phase noise for RF source in ~10 kHz BW

NOTE: energy-dependent horizontal orbit angle change in dipoles not an issue because of wide fan

Intensity Stability Sensitivities- cont.

Energy - cont.

- Energy-dependent beam size

For electron energy variations in lattice dispersion sections at frequencies > data integration time (i.e. **synchrotron oscillations):**

$$\sigma^2 = \varepsilon\beta + (\sigma_\delta\eta)^2 + (\eta\Delta E/E)^2 = \sigma_0^2 + (\Delta\sigma)^2$$

where σ_δ is natural energy spread of electron beam = ~0.1%

Also $\varepsilon \propto E^2$, but emittance change only happens for energy changes slower than damping times (~ms); synchrotron oscillations are too fast (0.1 ms)

e.g. $(\varepsilon\beta)^{1/2}$ = ~350 μm, $\eta\,\sigma_\delta$= ~100 μm for η = 0.1 m $\Rightarrow$ σ_0 = ~360 μm

$$\Delta\sigma/\Delta\sigma_0 < 0.1\% \quad \Rightarrow \quad \mathbf{\Delta E/E\ (rms) < \sim 10^{-4}\text{-}10^{-5}}$$

- Energy-dependent beam divergence

$\sigma'_{ph} = [\sigma'^{\,2}_{e-} + \sigma'^{\,2}_{\Psi}]^{1/2}$ $\quad$ $\sigma'_{e-} = [\varepsilon\gamma(s) + (\eta'\delta)^2]^{1/2}$ $\quad$ $\sigma'_{\Psi} \propto 1/E$

Unfocused beam size: $\sigma_{ph}(L) = [\sigma_{e-}^2 + \sigma_{diff}^2(\lambda) + L\,\sigma_{ph}'^{2}]^{1/2}$

unfocused beam intensity affected by both horizontal and vertical size change

Intensity Stability Sensitivities- cont.

Energy - cont.

- Energy-dependent photon emission

For **dipoles and wigglers**:

$F(\omega) \propto E_{e-}^{2} S(\omega/\omega_c)$ $\omega_c \propto E_{e-}^{2}$

For $\omega = 0.3\omega_c$:

$dF(\omega)/F(\omega) < 0.1\% \Rightarrow$ **$\Delta E/E$ (coherent) < 5×10^{-4}**

For $\omega = 3\omega_c$:

$dF(\omega)/F(\omega) < 0.1\% \Rightarrow$ **$\Delta E/E$ (coherent) < 2×10^{-4}**

For **undulators:**

$F(\omega) \propto E_{e-}^{2}$

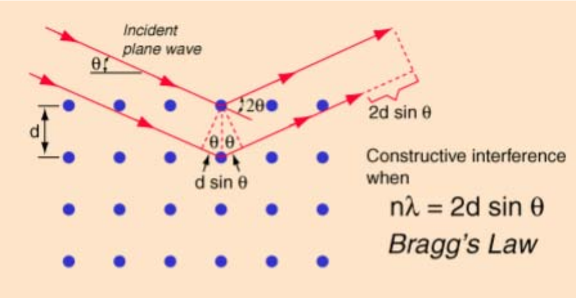
$dF(\omega)/F(\omega) < 0.1\% \Rightarrow$ **$\Delta E/E$ (coherent) < 10^{-3}**

Photon Energy Stability and Resolution

Photon energy resolution after monochromator:

Bragg reflection: $\frac{\Delta E_{ph}}{E_{ph}} = \frac{\Delta\theta}{\theta_B}$ where θ_B = ~5°-45° (~90-800 mrad)

For $\Delta E/E < 10^{-4} - 10^{-5}$, $\Delta y'_{ph}$ **< ~1-10 μrad**



Undulator line energy and width:

- Line wavelength $\lambda_n = n\,\lambda_u(1+K^2/2)/2\gamma^2$

  sensitivity to energy: $\mathbf{d\,\lambda_n/\,\lambda_n = -2\,\Delta E/E}$

- Line width = convolution of zero-energy-spread line width and that due to non-zero energy spread:

  zero-energy-spread line width $\Delta\lambda_n/\,\lambda_n$ = $\mathbf{1/nN_u}$ (FWHM), n = harmonic, N_u = # periods

  width from natural electron energy spread = $\mathbf{2 \times 2.35\,\sigma_{e-}}$ (FWHM = 2.35 σ)

  width from additional energy oscillations = $\mathbf{2 \times 2.35\, E_{e-}/E_{e-}(rms)}$

  $\Rightarrow$ total line width (FWHM) $\cong [1/(Nn)^2 + (4.7\,\sigma_{e-})^2 + (4.7\,\Delta E_{e-}/E_{e-}(rms))^2]^{1/2}$

Photon Energy Stability and Resolution - cont.

Undulator line energy and width - cont.

Total line width (FWHM) $\cong [1/(Nn)^2 + (4.7\ \sigma_{e-})^2 + (4.7\ \Delta E_{e-}/E_{e-}(rms))^2]^{1/2}$

For **$N = 100$, $n = 1$, $\sigma_{e-} = 0.1\%$**

$1/Nn = 10^{-2}$ $\quad$ $2.35\sigma_{e-} = \sim 2 \times 10^{-3}$ $\quad$ $\Rightarrow$ **natural line width = 1.1×10^{-2}**

For **$n = 7$**

$1/Nn = 1.4 \times 10^{-3}$ $\quad$ $2.35\sigma_{e-} = \sim 2 \times 10^{-3}$ $\quad$ $\Rightarrow$ **natural line width = 4×10^{-3}**

To limit increase in line width to <10% of width from natural energy spread:

$\Delta E/E$ (rms) < 10% natural line width = $\sim 4 \times 10^{-4}$ **for $n = 7$**

To limit for coherent line wavelength shift $d\lambda_n / \lambda_n$ to **$<10^{-4}$** **($N = 100$, $n = 7$)**

$\Delta E/E$ (coherent) < $\sim 5 \times 10^{-5}$

for 10^{-5} shift $\Rightarrow$ $\Delta E/E$ (coherent) < $\sim 5 \times 10^{-6}$

$\Rightarrow$ ϕ_{max} **< 0.01°** for SPEAR $\qquad$ Δf_{RF} **< 2.5 Hz** for f_{RF} = 500 MHz

Timing and Bunch Length Stability

Bunch time-of-arrival stability (Δt_{bunch}):

Δt_{bunch} < ~0.1 of critical time scale in experiment **(pump-probe sync, etc.)**

- or -

Δt_{bunch} < ~0.1 σ_{bunch}

whichever is larger

(σ_{bunch} = ~5-50 ps for rings, 100 fs for linac FELs and ERLs)

Time-of-arrival variations caused by energy oscillations:

$$\Delta t_{bunch} = \frac{\Delta\phi\ (\mathrm{rad})}{\omega_{rf}} = \frac{\alpha_c}{\Omega_s}\frac{\Delta E}{E}(\mathrm{coher}) \quad \Rightarrow \quad \Delta E/E\ (\mathrm{coherent}) < 2 \times 10^{-5}$$

or Δt_{bunch}~<10% σ_{bunch} in SPEAR 3 (σ_{bunch} = 17 ps)

Bunch length variations associated with changes in energy spread cause beam size variation:

$$\Delta E/E\ (\mathrm{rms}) < 10^{-3} \Rightarrow \Delta\sigma_{bunch} < 5\%\ \sigma_{bunch}$$

Lifetime

- **Lifetime contributors:**
  - quantum lifetime
  - gas scattering lifetime (Coulomb, bremsstrahlung)
  - Touschek lifetime
  - ions and dust particles
- **Touschek often dominant lifetime factor:**

$$\tau_{\text{Touschek}} \propto \frac{\sigma_{x'}\sigma_x\sigma_y\sigma_s\gamma^3\left(\delta p/p\right)^2}{N}$$

$\delta p/p$ = ring momentum acceptance   N = number of particles in bunch

$\Rightarrow$ **control and stabilize bunch volume**

e.g. increase vertical coupling, lengthen bunch with harmonic cavity

- **Ion trapping prevented by having gap in bunch fill pattern**
- **Top-off injection can solve lifetime woes**

Stability Tolerances

- Tolerance budget for electron beam parameters contributing to instability of a specific photon beam parameter can be derived from stability sensitivities, assuming random uncorrelated effects:

$$\sqrt{\sum_{i=1}^{n}\left(\frac{p_{tol}}{p_{sen}}\right)_i^2} < 1$$

p_{tol} = tolerance for parameter p, p_{sen} = sensitivity to parameter p

- e.g., to obtain <0.1% intensity stability, must reduce tolerances for orbit, beam size and energy stability below their sensitivity levels by ~1/√3 (0.57)

- Can increase tolerance for difficult parameters by reducing tolerance for easy parameters

Stability Requirements for Storage Rings - Summary

experiment parameters	beam orbit	beam size	beam energy/ energy spread
< 0.1% intensity steering to small samples	$\Delta x,y < 5\% \ \sigma_{x,y}$ $\Delta x',y' < 5\% \ \sigma'_{x,y}$	$\Delta\sigma_{x,y} < 0.1\% \ \sigma_{x,y}$ $\Delta\sigma'_{x,y} < 0.1\% \ \sigma'_{x,y}$	$\Delta E/E$(coher) $< 10^{-4}$ $\Delta E/E$(rms) $< 10^{-4}$
< 10^{-4} photon energy resolution	$\Delta x' <$ ~5 μrad $\Delta y' <$ ~1 μrad (undulator)		$\Delta E/E$(coher) $< 5 \times 10^{-5}$ $\Delta E/E$(rms) $< 10^{-4}$ (und n = 7)
timing, bunch length		$\Delta\sigma_t < 0.1\% \ \sigma_t$	$\Delta E/E$(coher) $< 10^{-4}$

Beam Stability for Linac FELs and ERLs

Linac FELs and ERLs are single-pass sources:

- do not have advantage of beam damping and steady state orbit that storage rings have (but they preserve low emittance from gun: diffraction limited **ε <~0.05-0.2 nm-rad** for multi-GeV)
- subject to pulse-pulse jitter in orbit and energy

Photocathode gun

- pulse-pulse charge stability: **< ~5%**
- emittance: <1.2 mm-mrad projected @ 1nC, <1 mm-mrad slice
  - **transverse uniformity of cathode emission**
  - **laser-rf synchronization**
  - **laser pulse shaping to minimize space charge effects**

Linac/Transport

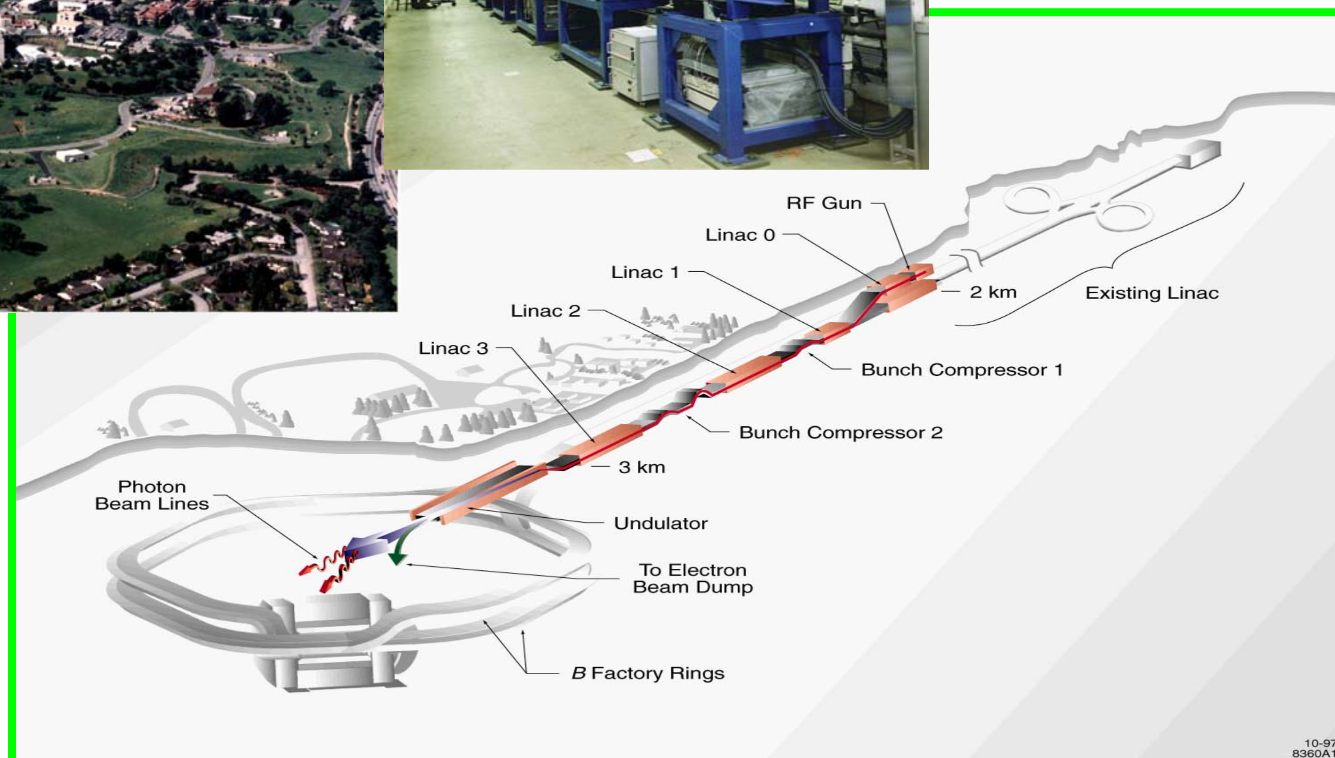
- energy stability: **< 0.1%**
- orbit stability: **< 10% σ**
  - **pulse-pulse rf phase stability**
  - **pulse-pulse rf voltage stability**
  - **laser-rf timing stability (<~1 ps)**

Beam at experiment

- position stability: **< 10% σ**
- pump-probe timing stability: **< bunch length**

Beam Stability for LCLS

$\sigma_x = \sigma_y = \sigma_s = \sim 24\ \mu m$
(~80 fs rms)
$\lambda_1 = 1.5$ Å



SASE: self-amplified spontaneous emission

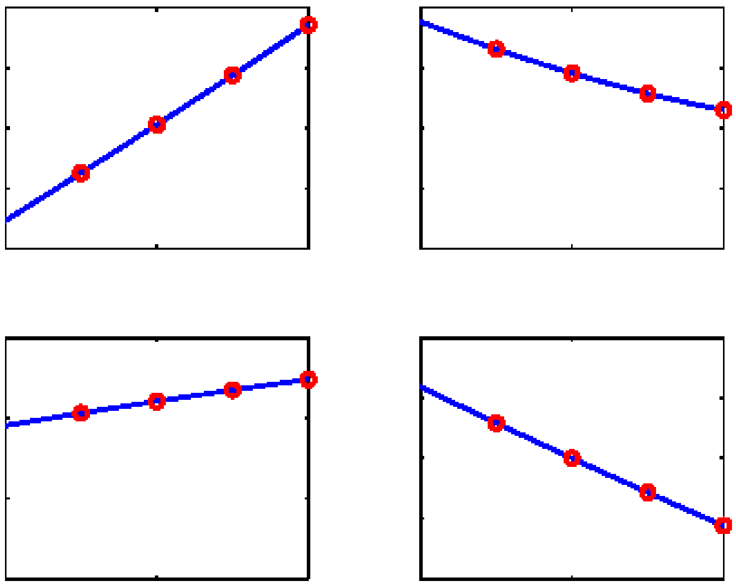
start-up from noise

Beam Stability for LCLS

from LCLS CDR

Seek < 12% bunch length/peak current jitter, < 0.1% energy jitter at undulator

sensitivity to gun timing jitter



Beam energy, $\langle \Delta E/E_0 \rangle$; rms bunch length, σ_z; rms energy spread, $(\Delta E/E_0)_r$ undulator arrival time jitter, $\langle \Delta t_f \rangle$; all versus gun-timing jitter, Δt_0. A 1.8-ps timi causes a 12% bunch length (or peak current) jitter. A 1.3-ps gun timing jitter ca 0.1% relative electron beam energy jitter in the undulator.

sensitivity to charge jitter

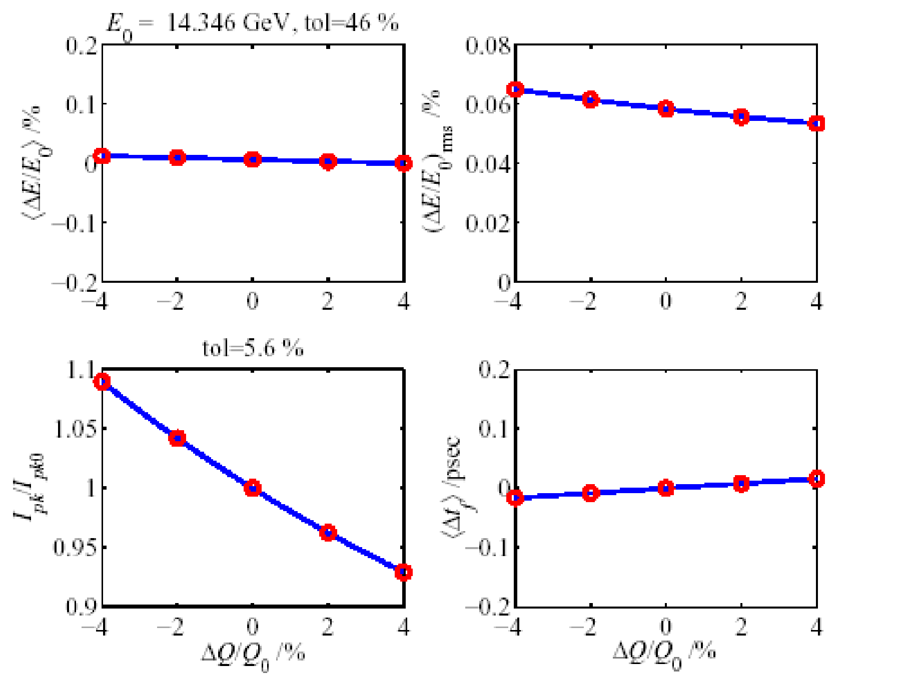


Figure 7.9 Same plots as **Figure 7.8**, but versus relative charge jitter, $\Delta Q/Q_0$, at the gun. A 5.6% charge jitter causes a 12% peak current jitter. The beam energy is, for all practical purposes, insensitive to charge.

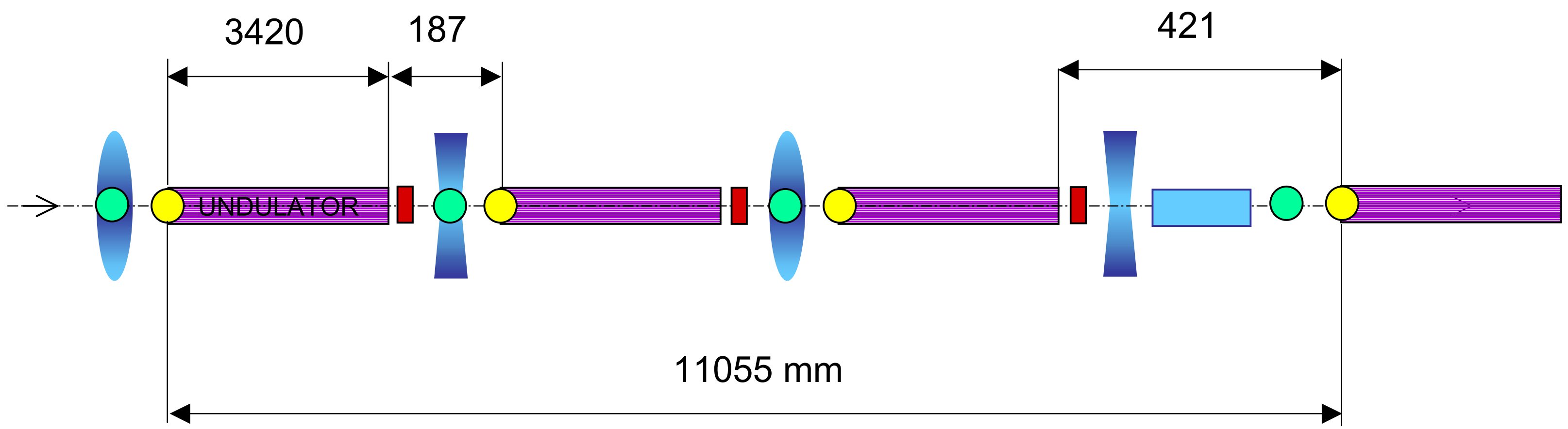
Conclude: <1.3 ps gun timing jitter <5% charge jitter

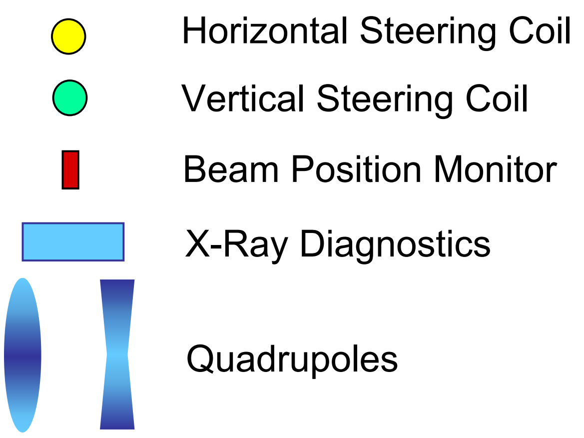
Beam Stability for LCLS - cont.

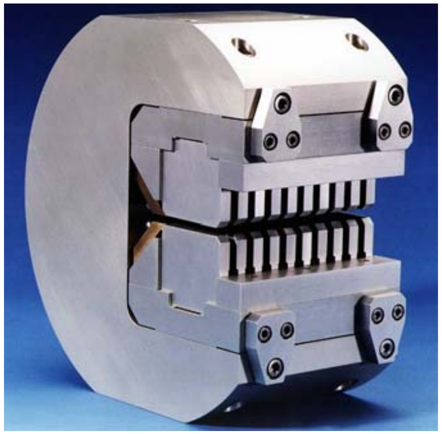
Tolerance budget for various parameters based on sum of random uncorrelated effects

Parameter	Symbol	$\lvert\Delta I/I_0\rvert < 12\%$	$\lvert\langle\Delta E/E_0\rangle\rvert < 0.1\%$	Unit
mean L0 rf phase (2 klystrons)	φ_0	**0.10**	0.10	S-band deg
mean L1 rf phase (1 klystron)	φ_1	**0.10**	0.10	S-band deg
mean LX rf phase (1 klystron)	φ_X	**0.30**	0.8	X-band deg
mean L2 rf phase (28 klystrons)	φ_2	**0.07**	0.07	S-band deg
mean L3 rf phase (48 klystrons)	φ_3	1.0	**0.07**	S-band deg
mean L0 rf voltage (1-2 klystrons)	$\Delta V_0/V_0$	**0.10**	0.10	%
mean L1 rf voltage (1 klystron)	$\Delta V_1/V_1$	**0.10**	0.10	%
mean LX rf voltage (1 klystron)	$\Delta V_X/V_X$	**0.25**	0.25	%
mean L2 rf voltage (28 klystrons)	$\Delta V_2/V_2$	0.10	**0.07**	%
mean L3 rf voltage (48 klystrons)	$\Delta V_3/V_3$	1.0	**0.05**	%
BC1 chicane	$\Delta B_1/B_1$	**0.02**	0.02	%
BC2 chicane	$\Delta B_2/B_2$	**0.05**	0.05	%
Gun timing jitter	Δt_0	1.3	**0.7**	psec
Initial bunch charge	$\Delta Q/Q_0$	**2.0**	5.0	%

Beam Stability for LCLS - cont.







Orbit Straightness in Linac FEL Undulator

To achieve SASE:

- Photon beam must overlap electron beam

  $\Rightarrow$ photon-electron alignment to within **< σ** in undulator

- Slippage between electron and photon path lengths = λ_{rad} in 1 undulator period

  $\Rightarrow$ extra slippage over 1 gain length **< 5% λ_{rad}** (L_G= 4.5 m = 3 x 10^{10} λ_{rad} for LCLS)

$\Rightarrow$ beam overlap criterion dominant for long λ (IR, UV)

beam slippage criterion dominant for short λ (X-ray)

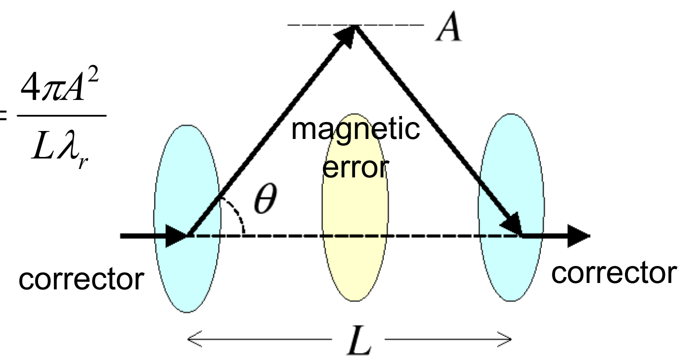
Straightness Tolerance

	LCLS	VISA	LEUTL	
A	3.2	50	100	microns
L	3.5	0.5	2.8	m
λ_r	0.15	800	380	nm
$\Delta\varphi$	245	78	118	mrad
L_G	4.5	0.17	0.75	m
$\Delta\varphi$ L_G/ L	315	27	32	mrad/L_G
$\sigma_{x,y}$	27	61	120	microns

Tolerance from Path Length Change

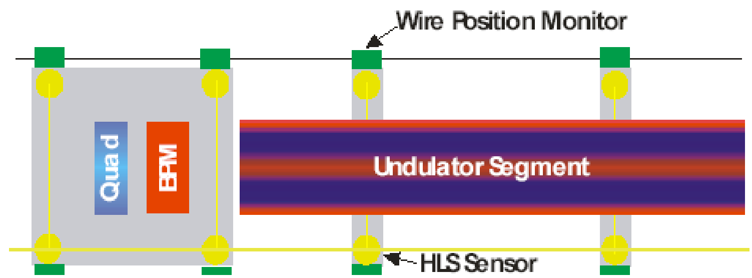
Tolerance from Overlap

$$\Delta\varphi = \frac{2\pi}{\lambda_r}\left(\frac{2A^2}{L}\right) = \frac{4\pi A^2}{L\lambda_r}$$

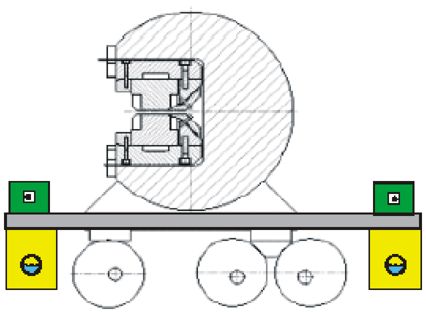


FEL Undulator Position Stability

LCLS undulator position monitoring and control



Monitoring System Layout, HLS (yellow), Wire System (green)



WPM

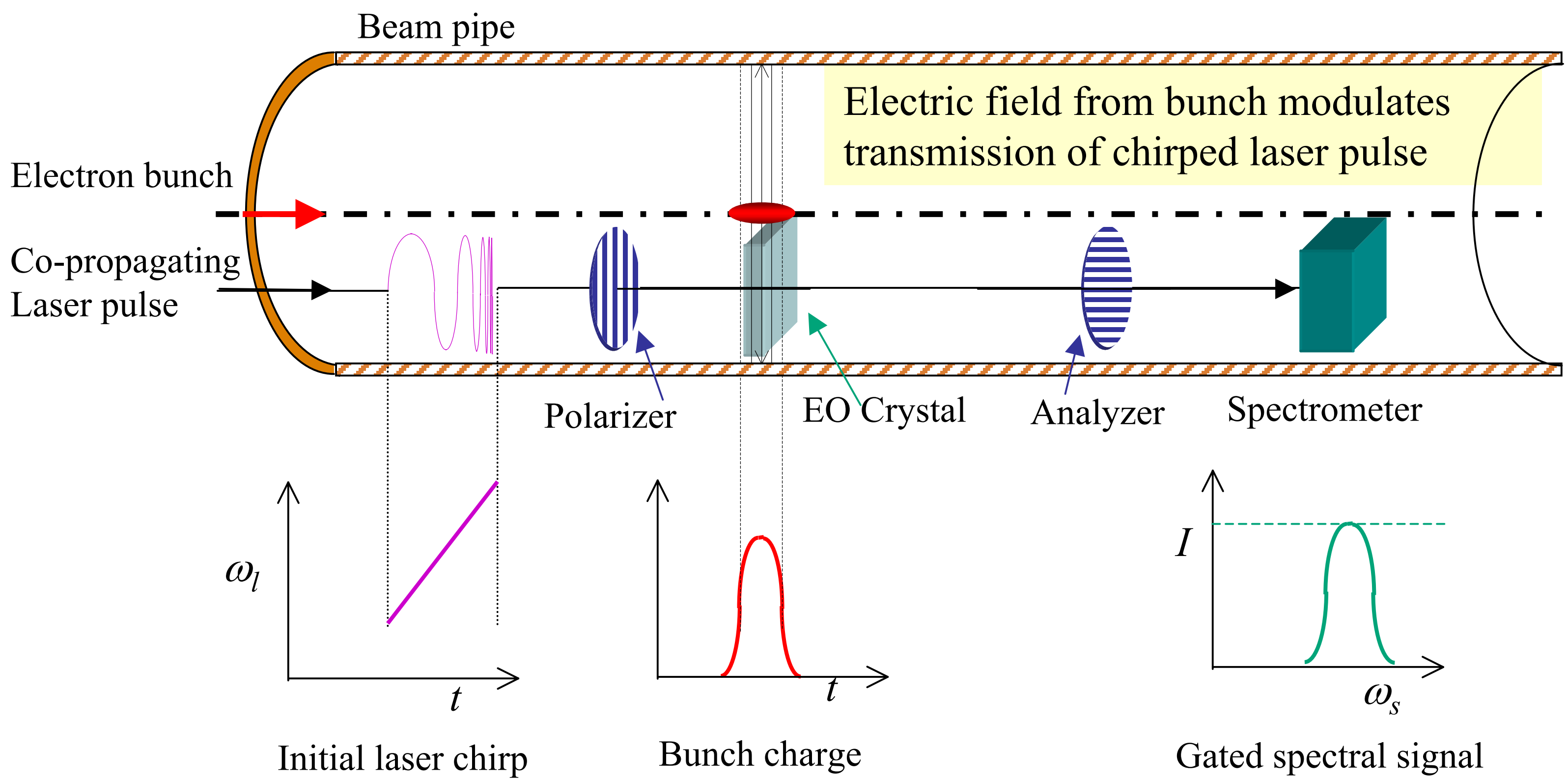
HLS

- 140 MHz signal transmitted on wire; sense horizontal position with 4-antenna pickup at BPM
- Hydrostatic leveling system (HLS) senses vertical position
- Cam movers maintain position

resolution **~100 nm for wire, ~1 μm for HLS**

Single-shot Femtosecond Bunch Length and Timing Measurement

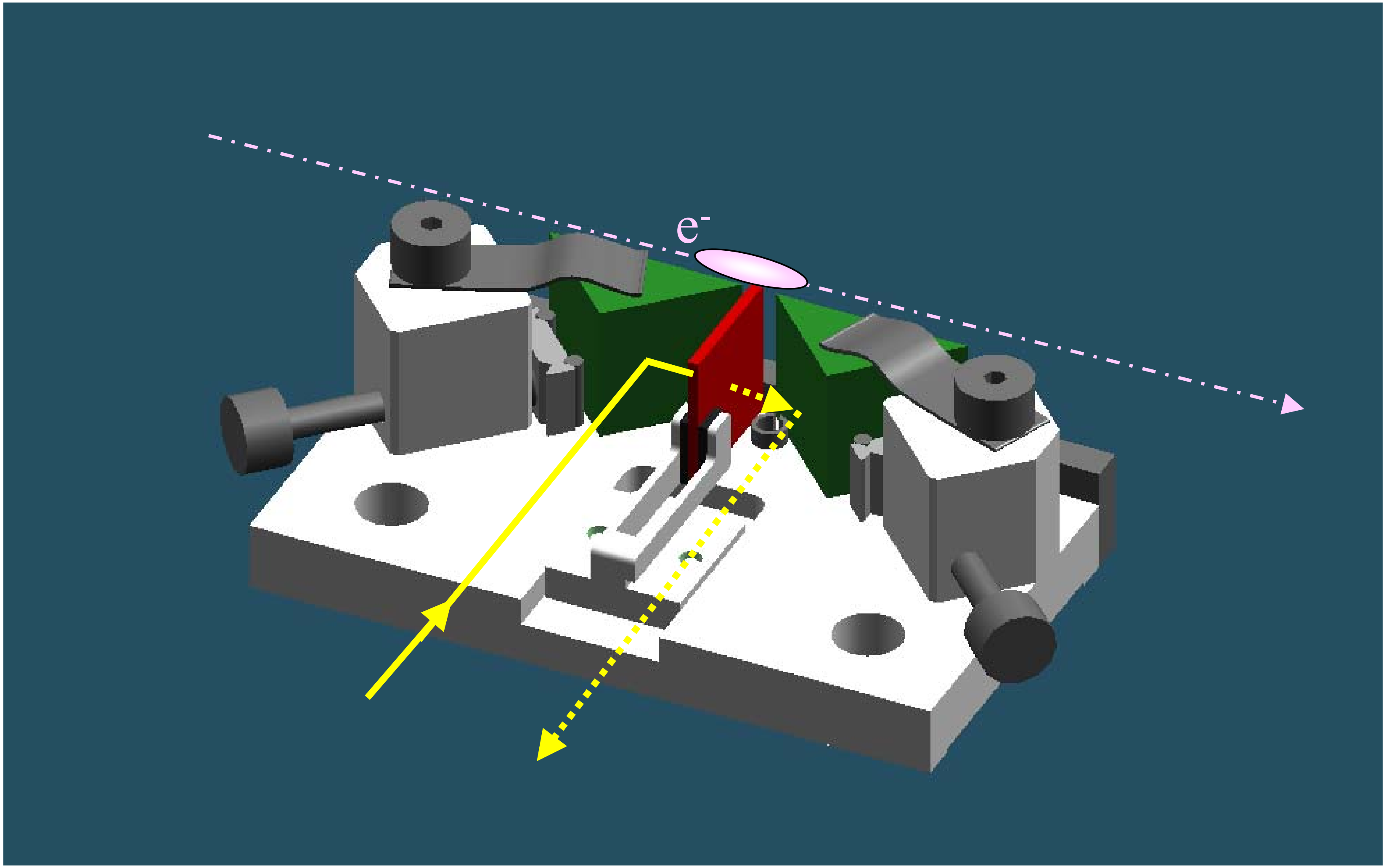
- Pump-probe timing stability of <100 fs extremely difficult to achieve
- Instead, measure shot-shot timing between pump laser pulse and electron beam
- Electro-optic detector can measure timing and bunch length:



from P. Krejcik, SLAC

Single-shot Femtosecond Bunch Length and Timing Measurement - cont.

Electro-optic Crystal Mount P. Krejcik, SLAC



Beam Stability for LUX ERL

- High brightness RF photocathode gun produces high-quality electron beam
- Accelerate in multiple passes through linac
  - Highly stable CW superconducting rf
  - 1 nC, 2 ps electron bunches at 10 kHz
- 2.5-3 GeV beam generates x-rays
  - 10-100 fs duration

Soft x-rays:

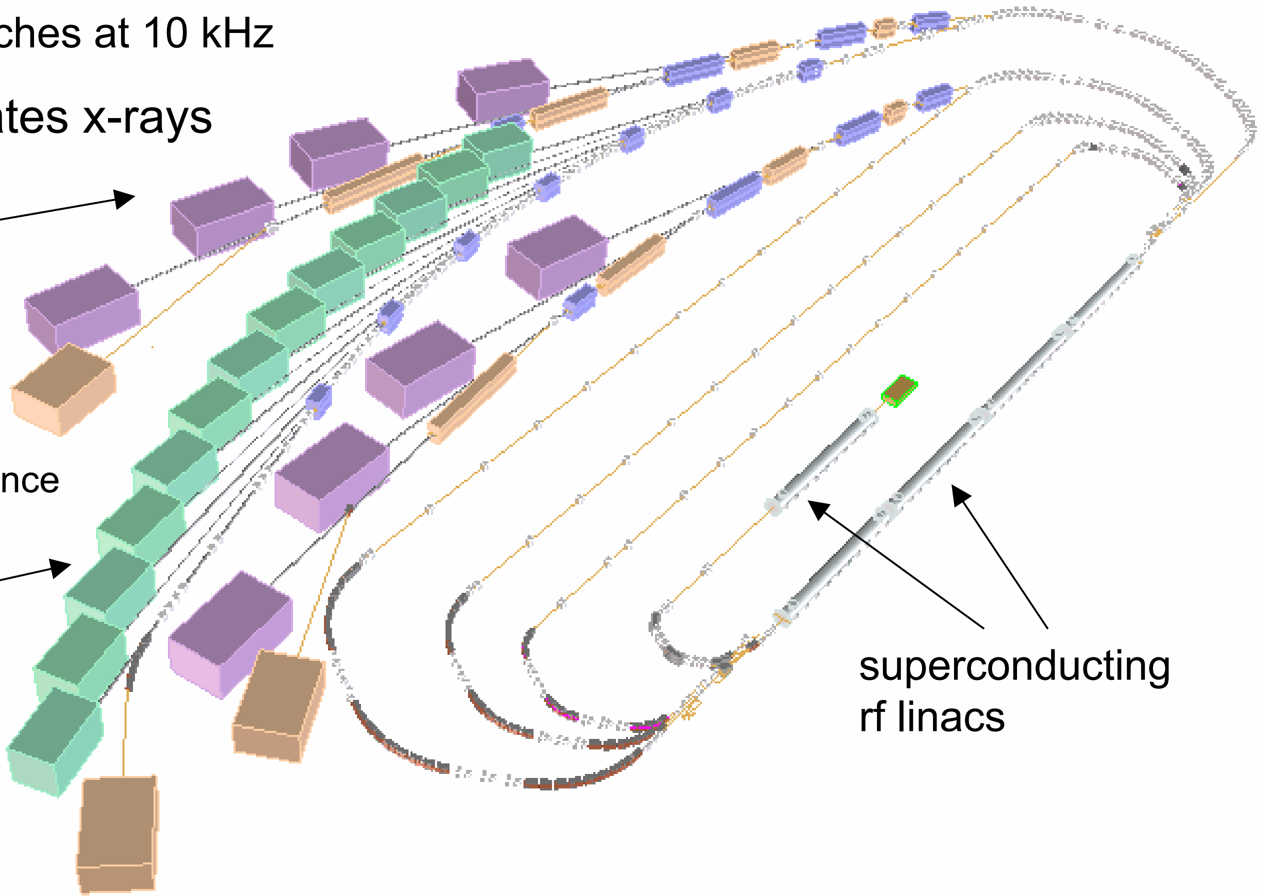
Seeded cascaded harmonic generation

- 20-1000 eV
- Spatial and temporal coherence
- 10-100 fs

Hard x-rays:

Spontaneous emission in narrow-gap short period IDs

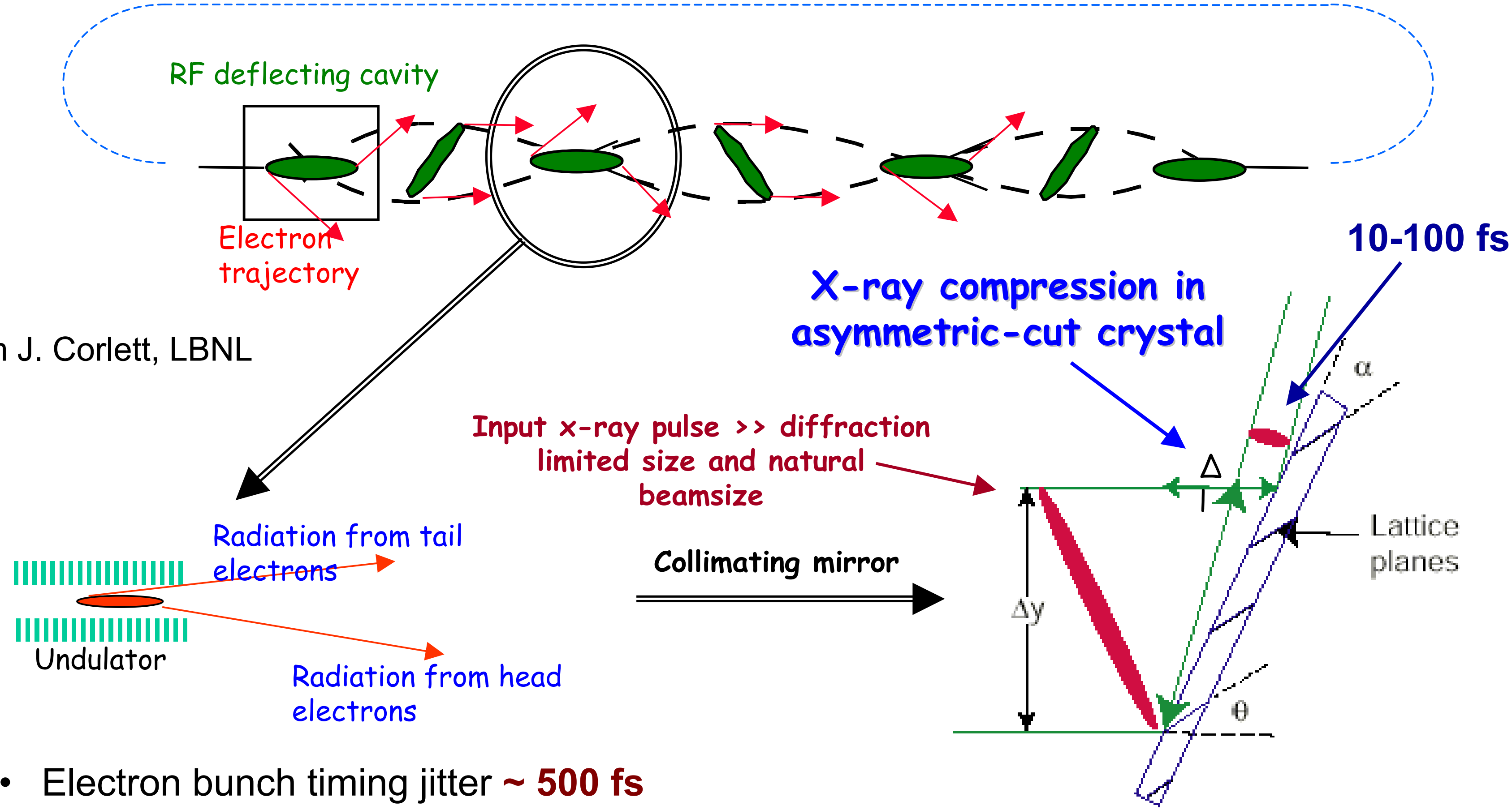
- 20-1000 eV
- 50-100 fs



Beam Stability for ERLs - cont.

Bunch compression at LUX (conceived by Z. Zholents)

from J. Corlett, LBNL



- Electron bunch timing jitter **~ 500 fs**
- Deflecting cavity phase stability **~ 0.05°**
  - 35 fs contribution from rf phase noise

Conclusion

3^{rd} generation stability requirements are stringent:

- intensity stability < 0.1%
- pointing accuracy < 5% beam dimensions
- photon energy resolution < 10^{-4}
- timing stability < 10% bunch length

$\Rightarrow$ **orbit < 1-5 μm, <1-10 μrad   beam size < 0.1 %   e- energy < 5 x 10^{-5}**

Requirements are becoming more stringent:

- for improved 3^{rd} generation sources, and for upcoming 4^{th} generation sources
- x 5-10 more stringent stability with beam source and beam line development

$\Rightarrow$ **orbit < .1-1 μm, <.05-.5 μrad   beam size < 0.01 %   e- energy < 5 x 10^{-6}**

- faster data acquisition time-scales
- fast-switched polarization, ID changes
- short bunch machines present pump-probe timing sync challenge: **<100 fs**